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CR 160091

(NASA-CR-160091) MICROWAVE SYSTEMS ANALYSIS, SOLAR POWER SATELLITE Final Report (Axiomatix, Marina del Rey, Calif.) 110 p HC A06/MF A01 CSCL 22B

N79-16892

Unclas
G3/15 13923

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MICROWAVE SYSTEMS ANALYSIS
SOLAR POWER SATELLITE

FINAL REPORT

Contract No. NAS 9-15240B

Prepared for

NASA Lyndon B. Johnson Space Center
Houston, Texas 77058

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Axiomatix Report No. R7901-1
January 8, 1979

TABLE OF CONTENTS

Page

LIST OF FIGURES

		Page
	103

1.0 INTRODUCTION

The purpose of the active alignment scheme is to automatically maintain the array of the Microwave Power Transmission System (MPTS) by individually aligning each subarray to one rotating laser beam plane. The reason for this requirement is that the beam efficiency, which is the percentage of collected energy by the rectenna compared to that radiated, is highly dependent on the antenna pattern generated by the array. One of the crucial parameters for a passive array is the flatness of the radiating array face which establishes the phase reference. This specification is not necessarily critical for a retrodirective pilot beam phase conjugation scheme where the proper phase relationships are generated at each power module, but considering the complexity involved and the subarray pointing requirements which still exist, it is reasonable to attempt to achieve the flatness by proper design considerations so that, inherently, flatness is maintained.

It is most important to use structural designs and materials which will simplify the construction and adjustments to attain flatness. The presently proposed MPTS structure uses a large primary structure on which a secondary support structure is placed. And on this secondary structure, the multiple subarrays composing the array will be mounted. In each case, the interfaces should be made as flat as reasonably possible to finally attain flatness at the subarray level. This requirement holds for the entire expected operating temperature range. Once this is successful, the next problem is developing a system which will maintain the array flatness by electronic means to constantly compensate for physical distortions.

The subject of this study has been to investigate various alternative active approaches to achieving and maintaining flatness for the MPTS array. As a result, a baseline active alignment scheme has evolved which includes subarray attachment mechanisms, height and tilting adjustments, service corridors, a rotating laser beam reference system, monopulse pointing techniques, and the design of a beam-centering photoconductive sensor.

The ideas outlined in this report are preliminary and basically compatible with the current design philosophies. As the Solar Power

Satellite design progresses, it is hoped that these ideas will evolve into more definitive concepts which can be readily implemented into the actual active alignment subsystem.

2.0 REQUIREMENTS FOR AN ACTIVE ALIGNMENT SCHEME

The goal of this study is to investigate various methods for achieving an active alignment scheme for the Microwave Power Transmission System (MPTS) of the Solar Power Satellite (SPS). The results described herein are a summary of the basic concepts developed in coordination with other related studies and therefore should be compatible with the present program with minimal adaptations.

The active alignment scheme for the MPTS array involves two procedures. First, the flatness of the phased array must be achieved in order to minimize phase errors which degrade the beam efficiency of the transmitted power. A rotating laser beam reference plane is proposed to establish this flatness over the large distances required (1 km) within the slope tolerances of the approximately 7000 individual subarrays (3 arc-minutes). In addition, this overall array must be pointed at the target rectenna within a slope tolerance of 1 arc-minute in order to maintain adequate phase conjugation margin for the retrodirective pilot beam technique. The proposed array pointing scheme involves a modified version of the monopulse tracking system and utilizes the same pilot beam signal from the rectenna. Together, this combination of flatness and pointing techniques provides a means for satisfying the strict requirements necessary to attain the high beam efficiencies that make the MPTS economically feasible.

2.1 Subarray Mounting Concept

One of the ancillary results of this early study on active alignment techniques is the preliminary design of possible coupling mechanisms which might be suitable for attaching the subarrays to the secondary structure. Some of the design requirements include the accommodation of thermal and mechanical distortions and the ease of fabrication and maintenance in a space environment. The final proposed design described in this report is only offered for consideration and represents an early baseline concept which can be used as a basis for the proposed active alignment scheme.

The MPTS array is composed of multiple subarrays attached to a support structure which is gimballed on a yoke connected to the main body

of the Solar Power Satellite. The configuration of the primary and secondary structures and the fabrication methods have already been studied in great detail, but the subject of the subarray attachment to the secondary structure has not yet been adequately addressed, especially in light of the subarray alignment requirements imposed. Therefore, a basic version of a subarray mount is described which at least provides for tilting adjustments and necessary alignment.

The subarray radiating surfaces are assumed to be assembled absolutely flat. No provisions are being considered in this report to adjust these surfaces once they are installed since the subarray is the smallest radiating unit considered. Flatness trimming adjustments would be feasible during assembly in a laboratory environment but would be too tedious and time-consuming in space. The tolerances involved at 2.45 GHz over the 10.4 m dimensions of the subarray are reasonable considering the availability of high-strength negligible expansion coefficient composites such as graphite epoxy. The subarray supports would probably be attached to a baseplate which maintains the subarray flatness since the waveguides of the radiating sticks, either metal or metallized composites, will not be sufficiently rigid.

The fabrication philosophy at this point is indeterminate since many different opinions exist. If the subarray is taken as an entity, it might be possible to assemble and test the subarray and subarray mount together in a laboratory environment. Especially critical to the alignment scheme is the proper operation of the optical sensors and the related variable-length adjustment motor drives. Installation can be reduced to simply inserting the center strut subarray mounting fixtures into the secondary structure, making manual optical alignment adjustments with the rotating laser beam references and, finally, attaching the appropriate power connections.

2.2 Thermal Distortions

The greatest concern on the part of the MPTS array alignment requirement is the effect of solar eclipses, which occur several times a year, on both the primary and secondary structures. It is anticipated that an extremely large temperature excursion of the order of hundreds of degrees Kelvin could occur within a few minutes. Some of the effects

that have to be considered involve thermal distortions which would suddenly disrupt the alignment of the subarrays and physical damage to the structure due to the abrupt thermal shock. Certain precautions are generally taken for critical items such as the power modules and pilot beam phase reference receivers, but the structures themselves will be open to minimize blockage for the radiative dissipation of waste heat from the subarrays and, therefore, they will be subject to the rapid temperature changes.

If the primary and secondary structures are fabricated from composites similar to graphite epoxy, the thermal conductivity and infrared emissivity play an important role in determining the temperature profiles that individual trusses in the structures must undergo. A rather thorough thermal analysis would therefore be warranted to study these effects, but techniques such as thermal insulation do exist to ameliorate the situation by increasing the thermal time constants and thereby minimizing the thermal shock.

The main areas of concern involving the active alignment scheme and the occurrence of a solar eclipse is the philosophy of maintaining alignment during the eclipse and the difficulties of adjusting to any warping of the supporting structures, both during and after the eclipse. If active alignment is continuously required, for example, provisions must be included to allow larger dynamic alignment ranges to accommodate the wide variations in truss lengths resulting from the thermal expansions and contractions in extremely large structures. Incorporating this increased adjustment length requirement should be considered as early in the conceptual design as possible since different designs naturally are more amenable to this particular modification than others.

The subarray three-point attachment center support strut concept outlined in this report, for example, will be shown to simplify height adjustments since it relies only on the center support, and tilting of the center support due to any warpage is readily readjusted by the azimuth-elevation controls. Another feature which is oriented to abrupt thermal distortion effects is the physical isolation obtained by the single-point support which relieves stresses that may arise from attaching the subarray at two or more points to the primary and secondary support structures that may be undergoing stresses from the effects of

thermal distortion. Therefore, in addition to the proper design considerations such as small thermal expansion coefficients for the structural members of the primary and secondary support structures, some additional thoughts on the subarray mounting concepts might be fruitful if they include compensating features for worst-case situations that may be encountered.

If the MPTS remains operative during the solar eclipse, by resorting to battery operation, the thermal shock and subsequent thermal distortions are naturally decreased substantially. However, this mode of operation does not imply that active alignment is not essential during this period since the array flatness is critical to proper performance. Therefore, the design which will satisfy the criterion must be able to cope with rapid thermal changes, both sensing misalignment and mechanically adjusting to compensate for distortions.

The time requirement for the complete alignment is important for the rotating laser beam reference system since only one laser beam rotates, and this rotation rate is relatively slow because photoconductive sensors and motor drives have long time constants. Thus, if operation during a solar eclipse is considered, a system analysis of the acceptable alignment time constants with respect to anticipated thermal distortion rate must be completed. Since redundant rotating laser beam reference systems will be available, it might be possible to operate all of them during the eclipse period to reduce the realignment time. However, special requirements to insure coincident laser planes must exist and periodic tests and adjustments performed. Another technique that may be considered is signal integration, where the laser beam rotates rapidly and the multiple signals are averaged over a period of time. For rapid physical changes, this averaging method at least permits uniform adjustments over the entire array. The key design parameter, of course, is the use of materials which have small coefficients of thermal expansion such that minimal adjustments have to be made. Then, thermal compensation designs such as using the center strut as a dissipative heat path through the universal ball-joint can be used to reduce the operational temperature ranges and therefore reduce the net thermal effects. This design can utilize the otherwise unwanted heat to warm the secondary structure and maintain a reasonable operating temperature range.

2.3 Mechanical Stress Relief

Mechanical distortions will arise from stresses developed during the assembly of the trusses into the primary and secondary structures. These stresses can readily be relieved if appropriate length adjustment mechanisms are included in the truss designs at the attachment points. However, since trusses have complex interactions between members, stress relief should be distributed along the entire length and breadth of the structure.

One means of isolating stress points is the use of the secondary structure which is situated above the primary structure, as shown in Figure 1. The attachments of the secondary structure to the primary structure can be designed so that adjustments can be easily made to align the secondary structures to a reasonable flatness requirement such that achieving the subarray flatness specification is greatly simplified. And extending this argument further, it is also imperative to obtain a degree of flatness for the primary structure, especially at the attachment points to the secondary structure.

Since a rotating laser beam reference system is being proposed as a means of providing an active alignment system for the subarrays, it is not unreasonable to use this system during the initial stages of fabrication, especially since it is a commonly used construction-leveling device. Fixtures to mount this system into both the primary and secondary structures during the assembly stages should therefore be provided at the required reference planes.

The attachment points between the primary and secondary structures, for example, would be one of the obvious reference planes. If these attachment points are made to coincide with this reference plane (by visual observation of the laser beam scanning by all the attachment points), it can then be assumed that a coarse degree of flatness exists. This evaluation procedure can be accomplished during construction but would be especially important after the primary structure have been established. and thermal and mechanical (stress) equilibrium has been established.

Similarly, this rotating laser beam system can next be used to achieve flatness for the attachment points connecting the subarrays to the secondary structure.

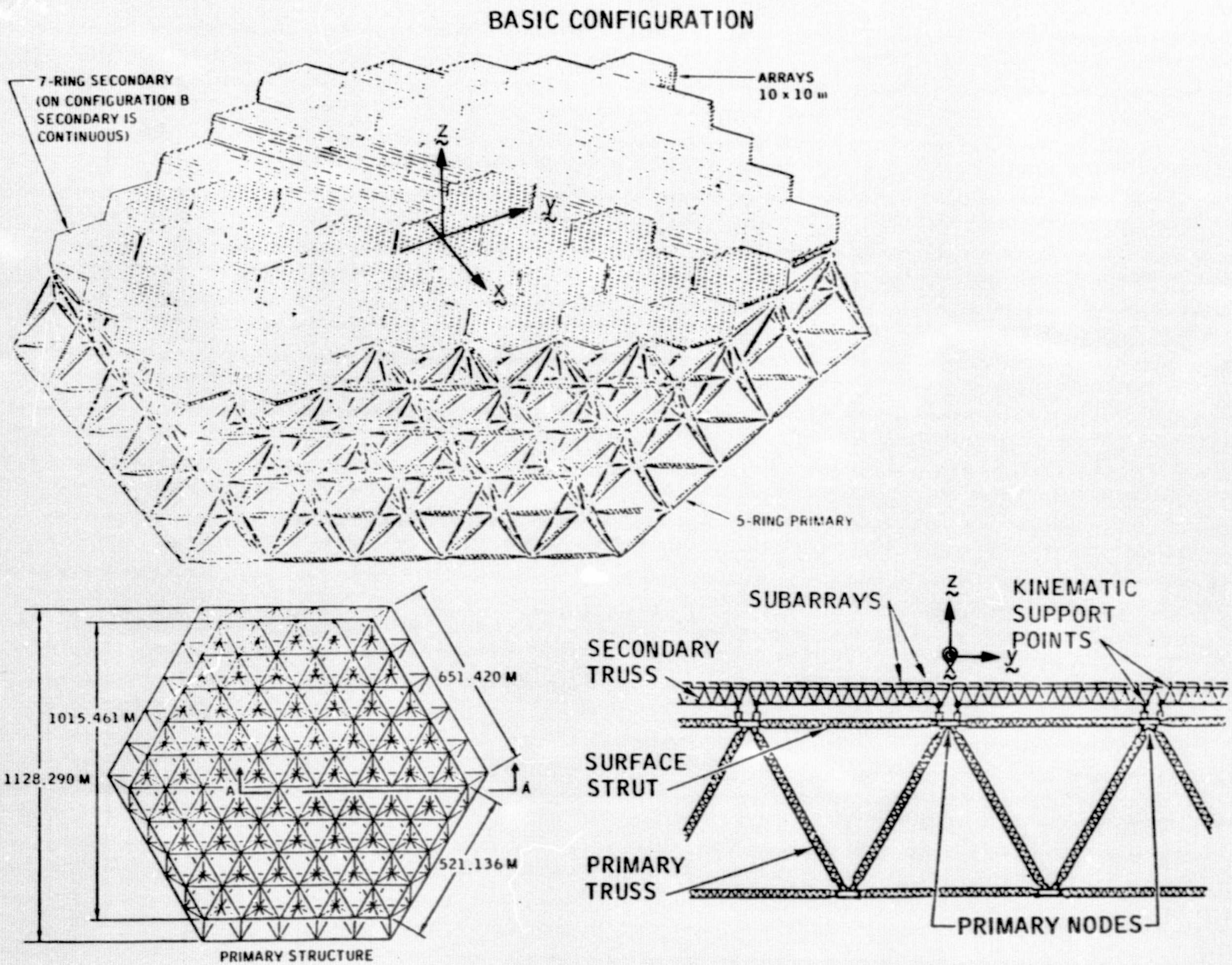

Figure 1. Primary and Secondary Structures of the MPTS Array

A means of minimizing the criticality of maintaining this flatness can be implemented by using keyed tubular mounts in which the subarray supports are inserted. These tubular mounts are oriented perpendicular to the face of the secondary structure, as depicted in Figure 2, and permit a wide latitude of height adjustment since the subarray support strut can be made arbitrarily long. Additional sections might even be screwed on in a manner similar to an oil drilling rig if additional lengths are required.

This single-point support concept also isolates mechanical stresses from the subarray itself and avoids the complexities of interacting subarrays if they were interconnected, as in the case of the membrane-within-a-frame concept.

The closest analogy of this single-support concept to terrestrial construction practices would be the technique used to create a level flooring for computer rooms. A support structure is raised above the uneven original floor by screw-type legs which are adjusted to the proper length. And conversely for the MPTS, if the support structure was warped, it is still possible to achieve flatness by adjusting the height of the single supports.

Further mechanical stress relief is obtained by using the triangular truss idea for adjusting the tilt of the subarray. Only two variable length mechanisms are required to control this tilting if they are placed orthogonal to each other.

Since this center strut three-point support subarray concept appears mechanically suitable (although other configurations may later be found to be more practical), it will be used to provide a baseline design on which to build an active subarray alignment scheme.

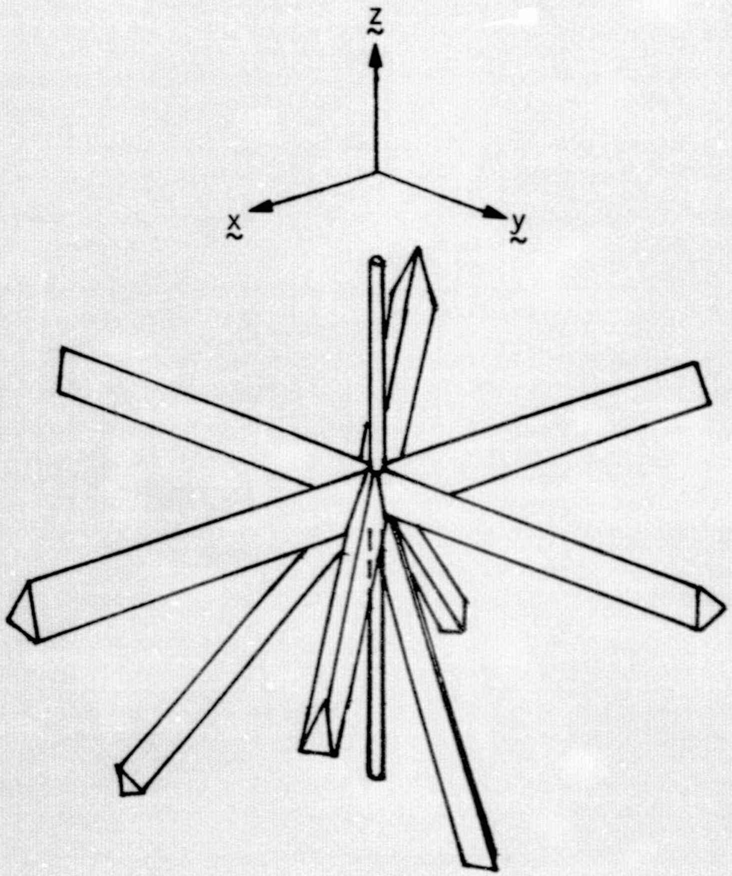

Figure 2. Modified Tetra Truss Beam Intersection with Tubular Mount

2.4 Continual or Periodic Realignment

The necessity for continual or periodic realignment can be answered most effectively by experience during actual operation of the MPTS. The only requirement that need be imposed is the inclusion of provisions to operate in either mode and practical design approaches to minimize valuable power consumption in the event that continuous operation is found to be essential.

The power requirement for a rotating laser beam reference plane system, for example, is 12 volts at 1.3 amperes for a total of 15.6 watts. The power requirements for the photoconductive sensors can be made small by using high impedance biasing circuitry such that only microamperes of current flow in the differential voltage resistance bridge circuits. Even though 21,000 optical sensors are required for the 7000 subarrays, at 28 VDC, the total electrical requirements are minuscule. The motor drives used to vary the lengths of adjustment trusses will not need to be continually activated if stepping motors are used. These stepping motors have the additional advantage of having a built-in mechanical locking capability because of the magnetic detents delineating the steps and the mechanical advantage of the gearing ratios. Because of the temporal sequencing of a slowly rotating laser beam, only a small sector of the array will be interrogated for flatness alignment at any instant of time so that the overall motor drive power consumption can be conservatively estimated to be one operating stepping motor, assuming some alignment is required.

After thermal and mechanical equilibrium have been reached, the schedule for the need for realignment can be assessed more realistically. Events such as solar eclipses which perturb the thermal equilibrium would definitely be classified as potential sources of misalignment, and the decision to maintain alignment would depend on such variables as continuous operation of the MPTS, the magnitudes of the array distortion, and the practicality of adjusting for short-term transient effects.

2.5 Realignment Time Period

The rotational speed of the rotating laser systems is variable and can therefore be used for both visual and active electronic alignment. The high rotational speed is useful for the initial alignment during fabrication for setting the attachment points of both the primary and secondary structures along parallel planes. At extreme ranges, it might be found useful to decrease the speed if the duration of the scanning beam is too short for adequate visual observation. The criterion for alignment would simply be the centering of the scanned beam at a marker on the attachment point and the subsequent manual adjustment by an astronaut if the beam is offset.

The active electronic alignment will have to be accomplished at a much lower rotational speed due to the relatively long response times of the photoconductive optical sensors and their associated motor drive circuitry. The type of motor drive circuitry has not yet been selected, but the basic principle of operation will be the detection of the laser beam by photoconduction. If one-half of the optical sensor is illuminated more than the other, its resistance is decreased. The polarity of this voltage differential determines the direction of motor drive, and the amplitude determines the number of steps required to achieve a null condition when the laser beam is centered on the sensor. Signal integration might be considered if averaging techniques and increased sensitivities are desired, which implies longer realignment time periods. Also critical to the analysis are the gearing ratios of the variable-length mechanism since these determine the length change per rotation of the screw. In any case, the realignment time periods should be of the order of seconds rather than minutes and therefore should be able to adapt to even the most extremes of conditions to be encountered, including solar eclipses.

3.0 CANDIDATE SUBARRAY SUPPORT STRUCTURES

One of the difficult aspects of attempting to develop a feasible active alignment system has been devising a suitable baseline design for the subarray support structure. The alignment techniques would most logically be integrated with the support structure to minimize the number of attachment points which are directly related to the mechanical and thermal stresses since they constrain relative motion between structures. The support structure must also provide a reliable means of maintaining flatness over the 1 km dimension of the MPTS, with an array tilt accuracy of 1 arc-minute and an individual subarray tilt accuracy of 3 arc-minutes.

The approach used in this study relies on maintaining flatness of the array by means of a rotating laser beam reference system, then pointing the entire array towards the direction of the retrodirective pilot beam by a monopulse tracking system with four monopulse elements to within the 1 arc-minute tilt accuracy. The phase conjugation retrodirective pilot beam concept would be independent of and therefore compatible with this design.

3.1 Three-Point Support

The three-point subarray support system uses the minimum number of attachment points yet provides sufficient flexibility to tilt the subarray in any desired direction. The basis for this concept is that a plane in space can be specified by three separate points contained in that plane. Since each subarray is an individual plane and the 7000 subarrays constitute a like number of independent planes, array flatness is achieved by simply aligning all these 21,000 points in the same plane in a similar manner. The three-point support then will be central to the active alignment technique.

The height of the center point in the subarray plane will be established first. Because the secondary support structure configuration has not yet been determined, the subarray support system must be adaptable to any possible suitable designs. For this reason, the proposed supporting mount for the subarray is reduced to a cylindrical tube which extends through the secondary structure and might be designed to actually be part

of the secondary structure itself. The tubular mount configuration was shown in Figure 2. The longitudinal axis of this cylindrical tube mount would be perpendicular to the secondary structure and therefore also normal to the array face. Since it will be difficult to assemble large structures in space without some distortion, the exact orientation of this tube within the secondary structure should be flexible; the subarray support, if designed properly, should be made to accommodate a reasonable amount of tilting in arbitrary directions. The first support member, then, will be a somewhat smaller cylindrical tube which is inserted into the large cylindrical tubular mount extending through the secondary structure, and the length of this cylindrical support provides alignment stability of the subarray with respect to the secondary structure. The length of the cylindrical support can be made arbitrarily long by the addition of more tubular sections, depending on the subarray height requirements above the secondary structure. In addition, the cylindrical support and tubular mount can be keyed in such a manner that the cylindrical support can only be inserted in one way such that the radiated microwave power polarization and phase are consistent over the face of the array.

This first cylindrical support is visually aligned with a rotating laser beam upon the photoconductive sensor which is located on the subarray face directly above the attachment point of the cylindrical support to the back of the subarray. This procedure can be accomplished by manual or automated means as long as a gearing mechanism is provided to adjust the height of the subarray.

The other two supports of the three-point support system will provide the tilting adjustment to the subarray face to position the other two attachment points into the rotating laser beam reference plane.

3.2 Center Support Strut

There is some question as to the optimum placement of this first cylindrical support strut. One concept, discussed in Section 3.5, places it at the edge of the subarray and places the other two supports at the corners of the opposite side to minimize thermal radiation blockage and simplify maintenance. The center support strut concept outlined in this section allows a more direct access to the back of the subarray for

maintenance purposes and opens the possibility of removing excess dissipative heat by thermal conduction since it is connected to the center of the subarray where the power modules are located.

The center support strut, because it supports the entire subarray, will be substantially larger than the two supplementary struts which tilt the subarray. Because of its size, it can provide a large heat path if sophisticated heat-pipe technology is exploited to first conduct the heat from the power modules to the large universal ball-joint coupling interface and subsequently another heat-pipe system to conduct the heat down the center strut, as sketched in Figure 3. Other heat-exchanging systems can be located adjacent to the tubular mount to help dissipate the waste heat. One advantage of this concept is that the heat is utilized by being distributed into the secondary structure, and therefore the temperature extremes and related thermal shock due to a solar eclipse are decreased.

The center support strut is connected to a universal ball joint which is a ball-and-socket arrangement that allows the subarray to tilt in any direction. This ball joint can be made arbitrarily large, for example, to increase the heat path into the center support strut. The variable-length mechanism, which controls the height of the subarray above the secondary structure, is located beneath the lower attachment points of the other two alignment struts which adjust for azimuth and elevation, as shown in Figure 4. The reason for placing this variable-length mechanism so low is to isolate the azimuth-elevation adjustments from the height adjustment to simplify the alignment procedure. Once the initial alignment during fabrication has been accomplished, this variable-length adjustment will maintain the center of the subarray in the rotating laser beam plane.

3.3 Azimuth-Elevation Adjustments

The azimuth and elevation adjustments are simply two variable-length struts placed orthogonally to each other to tilt the subarray about its universal ball joint in the desired direction. The strut itself constitutes a triangular truss beneath the subarray which supports it in the desired orientation. Since only two orthogonal struts are required, this leaves a large portion of the area beneath the subarray void of any structural members, which makes this particular concept

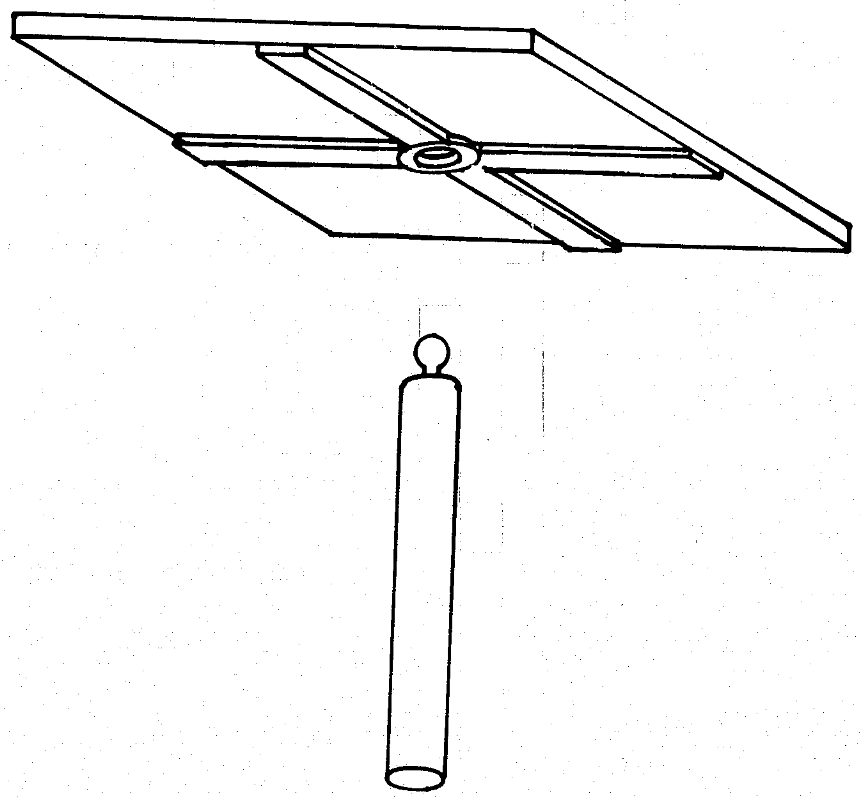

Figure 3. Universal Ball Joint Support

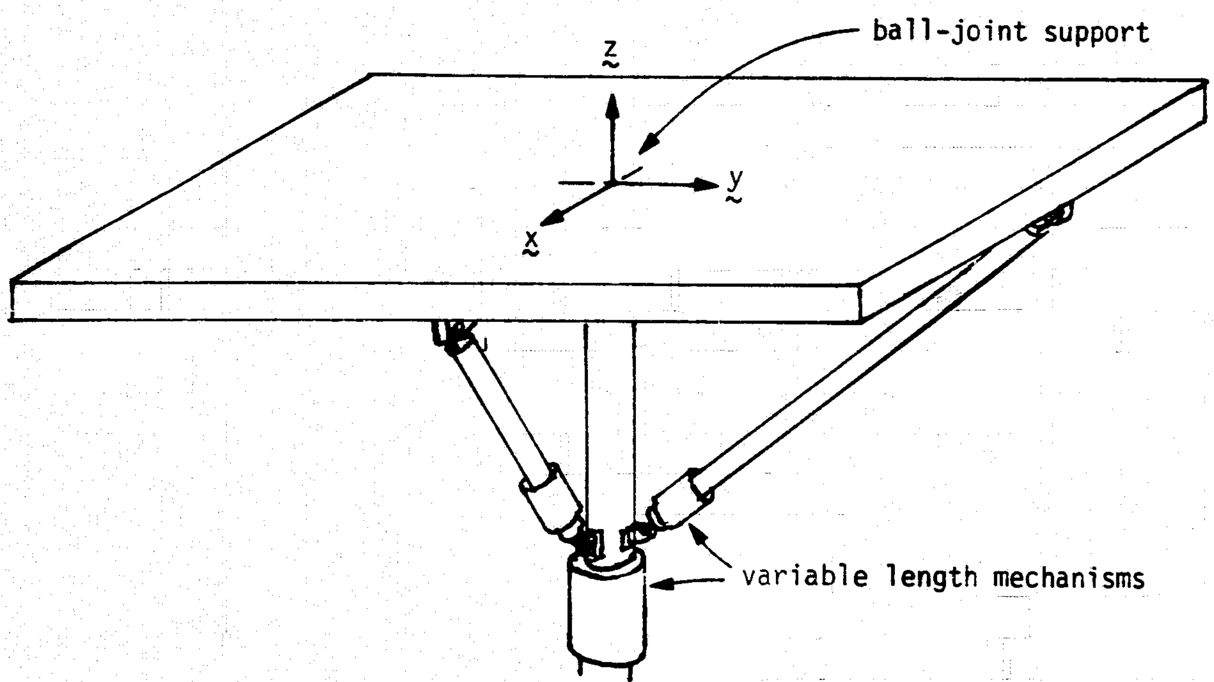

Figure 4. Azimuth-Elevation Strut Supports for the Subarray

suitable for a square matrix of service corridors.

The attachment points of the azimuth and elevation struts, which are identical in nature, can be two pinned U-clamp arrangements shown in Figure 5, since only two-dimensional motion is desired. If the lengths of the struts are varied, the tilt of the subarray is inherently changed since the triangular truss relationships are altered. This is valid in both orthogonal directions which are physically almost independent of each other. For this reason, the active alignment system can have both of these azimuth-elevation struts operating simultaneously with little iteration needed to achieve subarray alignment.

By virtue of the geometry of the triangular truss, it is also obvious that a high degree of tilt accuracy can be attained since the actual angular change about the center ball joint is reduced considerably with respect to the variable strut lengths. Accordingly, the tilt of the subarray will be determined primarily by the positional accuracy of the optical sensor.

3.4 Adaptation to Tilting

As was mentioned earlier, the tubular mount center support strut concept is amenable to a large degree of tilting in arbitary directions. This situation may be assumed to arise from any combination of conditions, from poor construction to thermal effects from a solar eclipse. The proposed three-point center support strut concept can adjust to tilting on an individual subarray basis, first with the height reference plane being reestablished, then the subsequent azimuth-elevation adjustments occurring.

An exaggerated tilted secondary structure case is shown in Figure 6 after realignment. As long as there exist enough variable-length capabilities in the height and azimuth and elevation adjustments, almost any distortion can be corrected. Again it should be emphasized that the cylindrical center strut length can be readily lengthened by adding another section, and this idea may be carried out for the azimuth-elevation struts also, although not as readily.

3.5 Proposed Alignment Scheme

A hypothetical alignment scenario might be as follows: The subarray with its three attached point supports (center and Az-El) is mounted into place by sliding the extended center main support strut into a

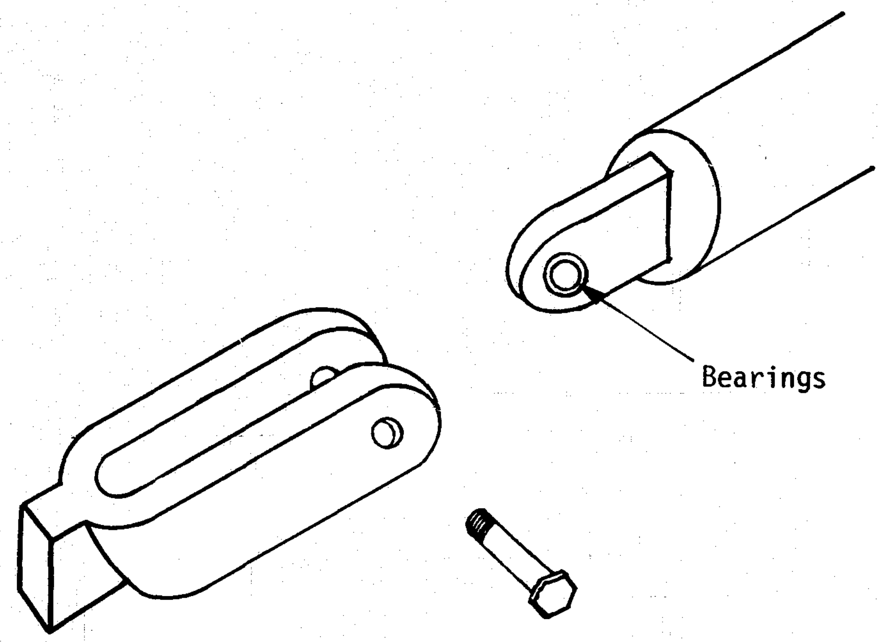

Figure 5. Pin and U-Clamp Attachment

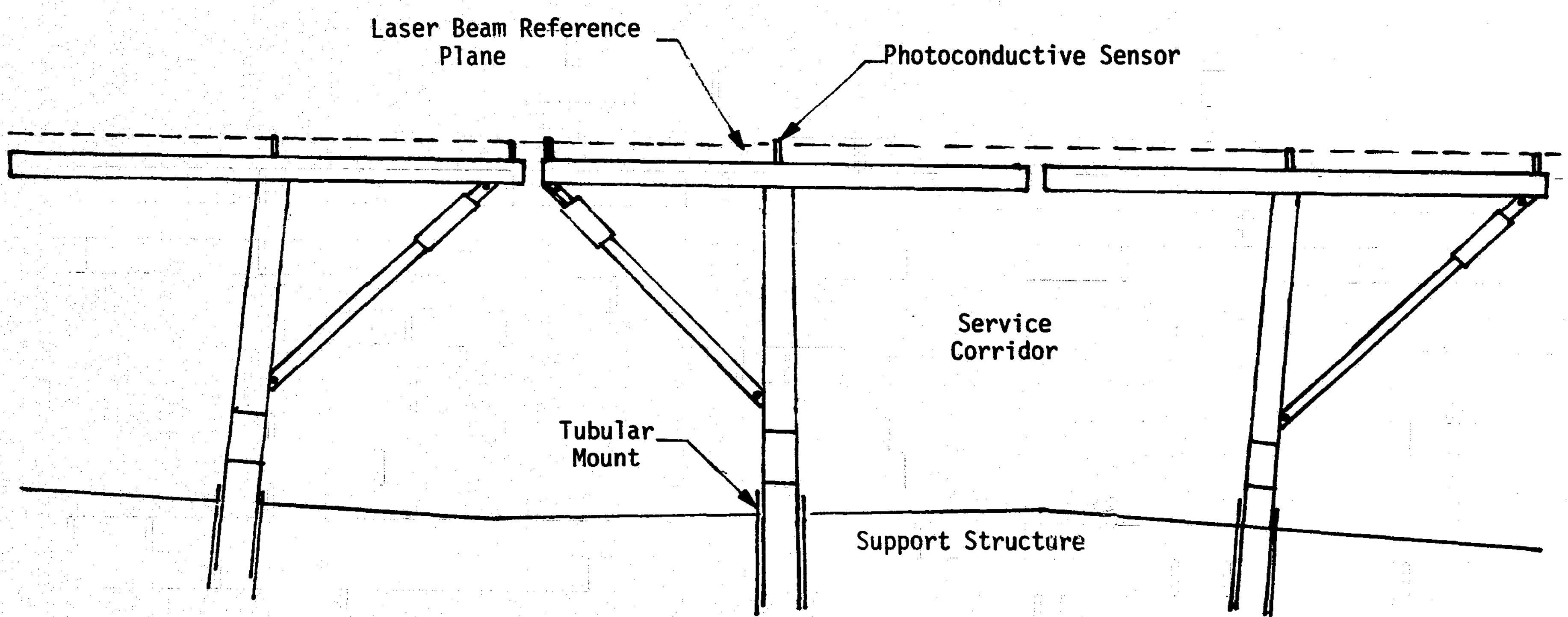

Figure 6. Exaggerated Tilting of Subarray Supports

cylindrical tube which is keyed to establish a specific orientation of the subarray. This tube, which is built into the supporting structures, provides the basic subarray mount, not unlike a fence post being inserted into a post hole. This approach has two attractive features. First, it provides a quick disconnect (and also connect) capability for ease in subsequent servicing. Second, it permits an initial mechanical height adjustment to accommodate the nonflatness of the supporting structure itself.

Although it has been established that adequate flatness can be achieved with existing technology, the cost and complexity of achieving this degree of flatness must be considered, especially if mechanical and thermal stresses are included. Since the subarrays are individually attached after the supporting structure has been built and thermal and mechanical equilibrium established, the totally independent three-dimensional adjustment capability of the three-point supports can be fully appreciated. Even if the mounting tube, for example, was tilted due to poor construction techniques, the tilted center support and the auxiliary Az-El supports can readily adapt to the situation by aligning to the laser beam reference plane.

By adjusting the position of the center support in the keyed mounting tube, the center of the centrally mounted photoconductive sensor above the universal ball joint support of the subarray can be made coincident with the laser beam reference. This would occur during the construction phase, where an observer on the subarray face would indicate the direction of movement necessary to attain alignment to another astronaut manually cranking a geared adjustment connecting the mounting tube to the center support. The face of the subarray would be slightly tilted toward the laser beam source to avoid any blockages by the laser side edge of the subarray. Once the center support was aligned, the center support would be locked into place. Fine adjustments of the position of the center support could then be manually cranked by the observer of the subarray face.

Next the Az-El support most perpendicular to the laser beam would be adjusted. Since three points in space can describe a plane, the subsequent adjustments of the Az-El supports will properly align the plane into the rotating laser beam reference plane. Again the observer on the

subarray face would visually align the laser beam with the center of the photoconductive sensors by means of a removable manual crank. Since this adjustment can be built into the attachment mechanism of the support to the subarray, this manual adjustment capability would be entirely independent of the variable-length mechanisms described elsewhere. Note that the universal ball joint at the center of the subarray is essential to this three-point support concept since it provides the central pivot point that makes the subsequent Az-El adjustments mutually independent of each other for simplicity of alignment. The central support alignment establishes a point in the laser reference plane, the addition of the second support alignment establishes a line connecting those two points into the laser reference plane, and the addition of the third support alignment finally establishes the plane by rotation about the line determined by the first two points. Thus, minimal readjustments are required, and the initial "tweaking" will suffice.

4.0 MAINTENANCE SERVICE CORRIDORS

Since the operational time of the MPTS is valuable, one of the critical aspects of the feasibility study was the maintenance time required to periodically service the MPTS and to repair it in the event of system failure. The radiation environment of the operating MPTS, being gigawatts of power, precludes servicing until the system is completely shut down. The ideal solution to the maintenance problem, then, is to minimize the shut-down time by incorporating special engineering designs into the structures and components to simplify repair and replacement, especially in light of the large number of subarrays and power modules in the MPTS.

One main consideration is easy access to the source of failure. Since the array is 1 km wide, access routes must be readily available through the array itself. A maze of established routes should be mapped out for ready reference to aid in the identification of failure locations. Once there, the crew should either be able to leave the service vehicle in close proximity to the failure or have manipulators which can adequately extend out from the vehicle to do the necessary repairs. The components should be readily replaceable as they are the most likely candidates to cause problems. There might also be occasions where an entire subsystem (a subarray, for example) may have to be replaced. This section outlines some maintenance philosophies which are suitable for the MPTS, especially with regard to existing active alignment concepts.

4.1 Square Matrix of Service Corridors

One of the results of the three-point single-support strut configuration has been the possibility of a square matrix of service corridors directly underneath the subarrays. As part of this study, a three-dimensional model of the three-point single-support configuration has been assembled to demonstrate the feasibility of these service corridors. This particular subarray attachment scheme is compatible with the original Boeing idea of service vehicles traversing underneath the main array for periodic inspection and replacement of damaged subarrays or components. The placement of the azimuth-elevation adjustment mechanisms can be such that a compact unit cell of four subarrays can be

formed with adjacent passageways. Using this square matrix of service passages, shown in Figure 7, each subarray is immediately accessible without having to compromise structural rigidity by removing support members.

If required, it may even be possible to replace an entire subarray using the quick connect/disconnect feature of the cylindrical single-support strut inserted into the tubular mount. The subarray separations might have to be slightly larger than the 10.4 m width of the subarrays to allow passage of the subarray under the plane of the subarrays. If the single-support strut can be readily removed, the subarray can be tilted to a diagonal position within the corridor to be transported down the service passageway by the service vehicle. Since the height of this corridor can range anywhere from 3 m to 7 m, this may be a viable approach.

The square matrix concept can extend like a maze throughout the MPTS, as shown in Figure 8, in a very orderly fashion. The subarrays would be individually accessible, without exception, by simply noting the grid locations and traveling directly down the appropriate passageways in the service vehicle and making the necessary repairs.

Availability of close access to the electronic components, especially the power modules located near the center of the subarray, makes the square matrix of service corridors especially attractive for quick maintenance since all of the work is done within 5 m of the service vehicle. Half of the components, in fact, are located within the service corridors if they are equally distributed. Very little blockage will arise from the azimuth-elevation adjustment struts since they are relatively small in size and attached at the edges of the subarray. In the event they are in the way, they can be easily disassembled by simply removing the pin from the U-clamp described earlier and replaced just as readily. And, since the height of the subarrays above the secondary array is not fixed, it is possible to adjust this dimension to provide adequate working space.

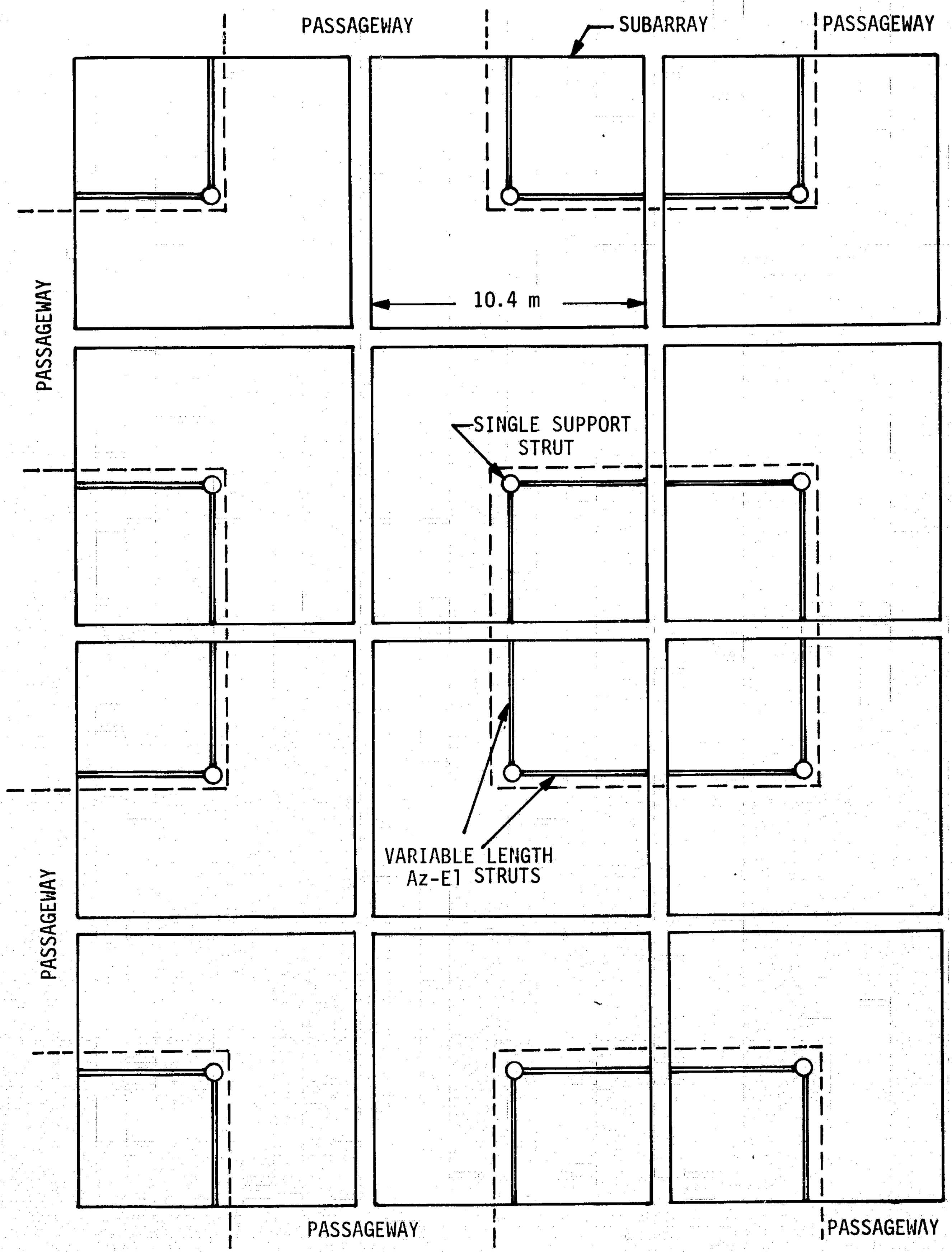

Figure 7. Top View of Array Showing Service Passageways Under Subarrays

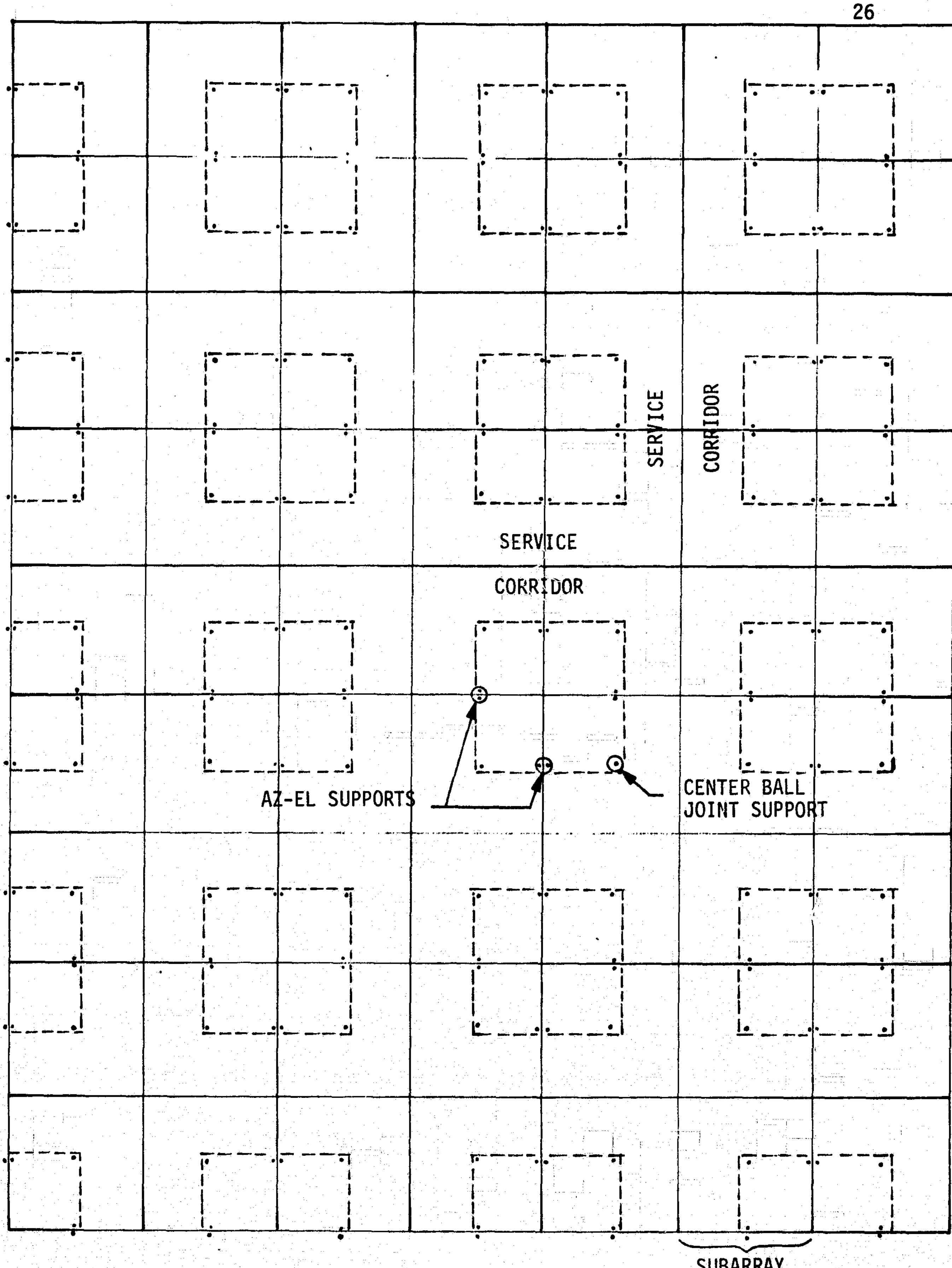

Figure 8. Array with Service Corridors
and AZ-EL Subarray Supports

4.2 Alternate Maintenance Concept

The maintenance concept presently envisioned by Boeing employs a cherry picker-type of manipulative mechanism inserted through the secondary structure to perform replacement operations. The secondary structural members and the subarray mounting scheme are both designed to accommodate this technique. A minimal number of trusses is used in back of the subarrays to simplify access to the power modules, which are the most likely candidates for failure and subsequent servicing. This configuration also minimizes the amount of blockage of the thermal radiation cooling on the back surface of the subarray.

The radiative cooling relies on the large temperature differential between the operating power modules and the cosmic background temperature, which is approximately 2.7°K. The radiative heat transfer relationship, on a simplistic basis, is proportional to the difference between the fourth powers of the absolute temperatures. Since the center subarrays will have 36 power modules, this type of dissipative heat transfer might not be adequate and supplementary thermal conduction might be required. However, further studies should be made concerning the thermal equilibrium conditions achieved for all subarrays since the 10 dB Gaussian illumination taper of the array produces a widely varying thermal environment, thereby complicating other aspects of the system design such as the subarray flatness alignment

One design approach is a three-point support structure similar to the center strut one that is being proposed. The primary difference is that, rather than having a central support with azimuth-elevation tilting adjustments, three supports are attached directly to the edges of the subarray in a triangular fashion. The secondary structure interface is designed to have structural members at the appropriate attachment points to the subarray yet maintain clearance for both maintenance and radiative cooling. Since the subarrays are 10.4 m square, this implies that the secondary structure will also have trusses that are approximately the same dimensions but triangular in shape. The subarray attachment mechanism will then connect the subarray to the secondary structure at these three overlay points. The most likely attachment mechanism will be a truss perpendicular to both the planes of the subarrays and the secondary structure, and this support truss would have a variable-length capability for alignment purposes.

At least one of the three support trusses will be required to be rigidly mounted to the secondary structure to maintain a fixed position. If all three were loosely connected, no height reference would exist, and the support structure would be unstable. In order to provide stability, something equivalent to triangular trusses must be employed to avoid rotational moments of inertia and subsequent collapse. This idea is related to the rigidly mounted center support concept where the center strut absorbs all rotational torques on the subarray. The other two supports then provide the tilting necessary to attain alignment, similar to the azimuth-elevation adjustments.

The height of the subarray above the secondary structure is relatively short to facilitate servicing by the cherry picker from behind the secondary structure. Another consideration for the closeness of the subarray to the secondary structure is the location of the center of mass which might affect movements of the array in the yoke.

In any case, this concept, although different, is compatible with the proposed active alignment scheme in that many of the related problems and solutions are similar and therefore adaptable.

4.3 Component and Subarray Replacement Techniques

The components, including power modules, waveguide sticks, phase conjugators and pilot beam receivers, will probably be designed on a modular basis such that they can be individually replaced. The test monitoring and power leads most likely will be attached with locking connectors. The ease of replacement, then, is really dictated by access and simplicity of attachment mechanisms.

One unknown at the present time is whether the replacement will be done manually by an astronaut or remotely by manipulator arms from the service vehicle. The repair problem is, of course, different in each case.

For the sake of an example, suppose an astronaut attached to a service vehicle by an umbilical cord approaches the rear of a troublesome subarray. The problem will have to be isolated earlier by means of adequate monitoring circuits since no test evaluations can occur during the maintenance procedure. Rather than spending valuable time on repairs, the astronaut will simply replace the errant item. For this reason, the power modules will probably be conspicuously mounted on the back of the subarray, attached to a thermal sink consisting of heat pipes which transfer heat through the ball joint of the center strut. Radiative plates on the power modules will provide additional cooling. Since as many as 36 power modules will exist on the centrally located subarray, they should be laid out on the heat sink in an orderly fashion and distributed such that large heat concentrations (and therefore higher temperatures) are avoided. The waveguide sticks composing the subarray face would be attached to this thermal plate, but thermal isolation might be seriously considered to avoid overheating the waveguides. The flatness of the subarray face itself will have to be measured and adjusted in a laboratory environment, either before assembly or after removal, since this can be a tedious, time-consuming process. Therefore, some provisions for subarray replacement, at least the waveguide stick array face, might be considered.

Replacement of a power module will require uncoupling at least one set of waveguide flanges which, for S-band, is not difficult for the case of an astronaut. The power module itself will have to be firmly mounted to the heat sink with many bolts and will prove to be more cumbersome.

5.0 VARIABLE-LENGTH MECHANISMS

The proposed active alignment scheme is based only on the variable strut length principle for the positioning and pointing of the subarray for three main reasons. First, by using a strut which extends from the center support to the edge of the subarray, higher alignment accuracies can be obtained because of the optical leverage of the three widely separated photoconductive sensors controlling the pointing of the subarray. Second, redundancy is easily implemented since many independent variable-length drives can be serially located along the strut. Third, by using gearing ratios, the angular displacement due to steps of a stepping motor can be very small so that the angular resolution is very high.

The variable-length mechanism is especially suited for the three-point support system since only three variable-length mechanisms are required to properly position the subarray. The proposed azimuth-elevation mount requires one variable-length mechanism to adjust the height of the subarray, another to independently adjust the azimuth direction, and the third one to adjust the orthogonal elevation orientation. In addition, the mechanical interaction between the three variable-length mechanisms is minimal for this three-point support configuration so that iterative adjustments are not necessary.

An added feature is the small physical size of the variable-length mechanism since it can be readily incorporated into a tubular strut, and the cross sections of the azimuth and elevation struts can be relatively small and therefore simplify the maintenance problem by reducing blockage. The center strut can be large since it supports the subarray and possibly provides a dissipative heat path.

5.1 Worm Gear Drive

The baseline variable-length mechanism is a worm gear driven by an electric stepping motor. There are some inherent advantages of this approach. One is the flexibility in the amount of extension since the worm gear can be made in arbitrarily long lengths. Another is that the mechanical resolution can be changed by selecting different numbers of threads per inch. And third, the power requirements are reduced since the motor does not need to be operated continuously, having magnetic detents for mechanical locking. The gearing ratios used can also be varied according to the specific application.

Various configurations can be devised for the worm gear drive. A representative one is shown in Figure 9, which shows a screw-type worm gear which moves longitudinally with the rotation of the screw. Relative rotation of the tubular strut is avoided by means of keyed inserts, shown in the adjacent cross-sectional view, which allows only linear movement along the strut. The electric motor depicted in the diagram can be a stepping motor and, in combination with the associated gearing mechanism, can increase the rotational torque to overcome frictional loads and also decrease the amount of linear motion per step increment of the stepping motor.

Motion in both directions is possible by reversing the voltage impulse inputs into the stepping motor as determined by the differential voltage signals of the optical sensor resistive bridge circuit. The two restraints are the length of the worm gear and the gap between the threaded portion of the strut and the motor. During installation, the variable-length mechanism will be set in the middle of the available length adjustment range so that maximum flexibility is assured. Rather than using only a few of these variable-length mechanisms along a strut with long worm gears, it might be more feasible to use more of these variable-length mechanisms in series since they can operate independently and therefore provide a greater degree of redundancy.

5.2 Serial Redundancy

The main concern with any type of mechanical moving mechanism in space is the fear of a failure which can hamper the mission. To maintain reliability and prevent the loss of an important function due to a mechanical failure, redundancy is employed wherever possible to reduce the dependence on the proper operation of a critical component. In the particular case of the active alignment scheme of the MPTS, this redundancy can be readily implemented by the serial placement of variable-length mechanisms along the appropriate struts. Since the rotation of the strut itself is constrained by the two pin and U-clamp attachments at both ends and the keyed structures within the variable-length mechanisms, the only allowed motion is linear along the strut axis. Thus, more than one variable-length mechanism can be built into the strut. Each of these variable-length mechanisms can be independently driven by its own optical sensor mounted above the strut attachment point on the subarray face, as

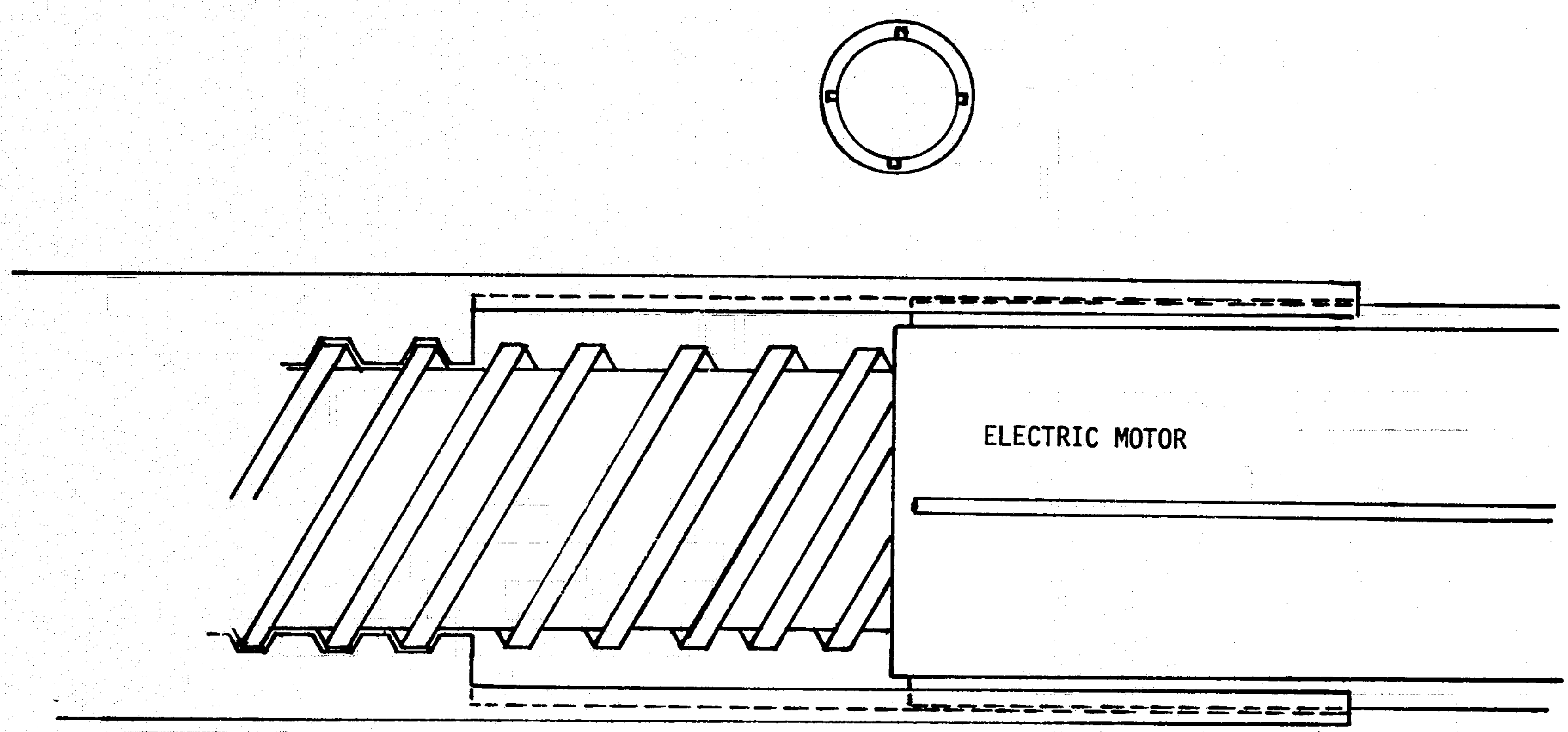

Figure 9. Candidate Variable Strut Length Mechanism for the SPS

shown in Figure 10, for the case of four redundant systems.

If all of the variable-length mechanisms are operating simultaneously, the length adjustment will be shared equally among all of the variable-length mechanisms operating. If one or more of the motors froze up and became inoperative, they effectively become part of the strut and the remaining units would perform the alignment functions. Replacement of the entire strut is simplified since only two pins (shown earlier in Figure 5) at the ends of the strut have to be removed and new electrical connections made by means of a multipin connector.

The cluster of more than one optical sensor should not pose a problem since the optical blockage problem discussed in Section 7.0 indicates that, with the judicious placement of the rotating laser beam system, almost all the sensors will see the laser beam. In fact, the redundancy in optical sensors actually alleviates some of the blockage problem since any one of the sensors in the cluster can align the subarray.

5.3 Coarse Adjustment Subarray Attachments

The initial adjustments of the subarray in order to achieve alignment are categorized under coarse adjustments since the amount of strut movement may be quite large. This adjustment during array assembly is completely independent of the variable-length mechanism used for fine tuning the active alignment.

There are actually two types of coarse adjustment for the three-point subarray support structure. The center support strut is inserted into the tubular mount and the height of the subarray center is aligned to the laser reference plane by altering the position of the strut within the tubular mount. One means of controlling the strut position would be a manual crank arrangement, which uses a long row of gear teeth on the center support strut and a circular cranking gear on the tubular mount to raise and lower it, as sketched in Figure 11. The long row of gear teeth also acts as a key to properly orient the subarray. Gearing ratios can be used to increase the mechanical advantage and more accurately control positioning. Once the central optical sensor is aligned with the laser beam, the center strut is locked into place. A unique locking method utilizing a series of collets will firmly anchor the tubular mount to the center support strut and also provide the intimate

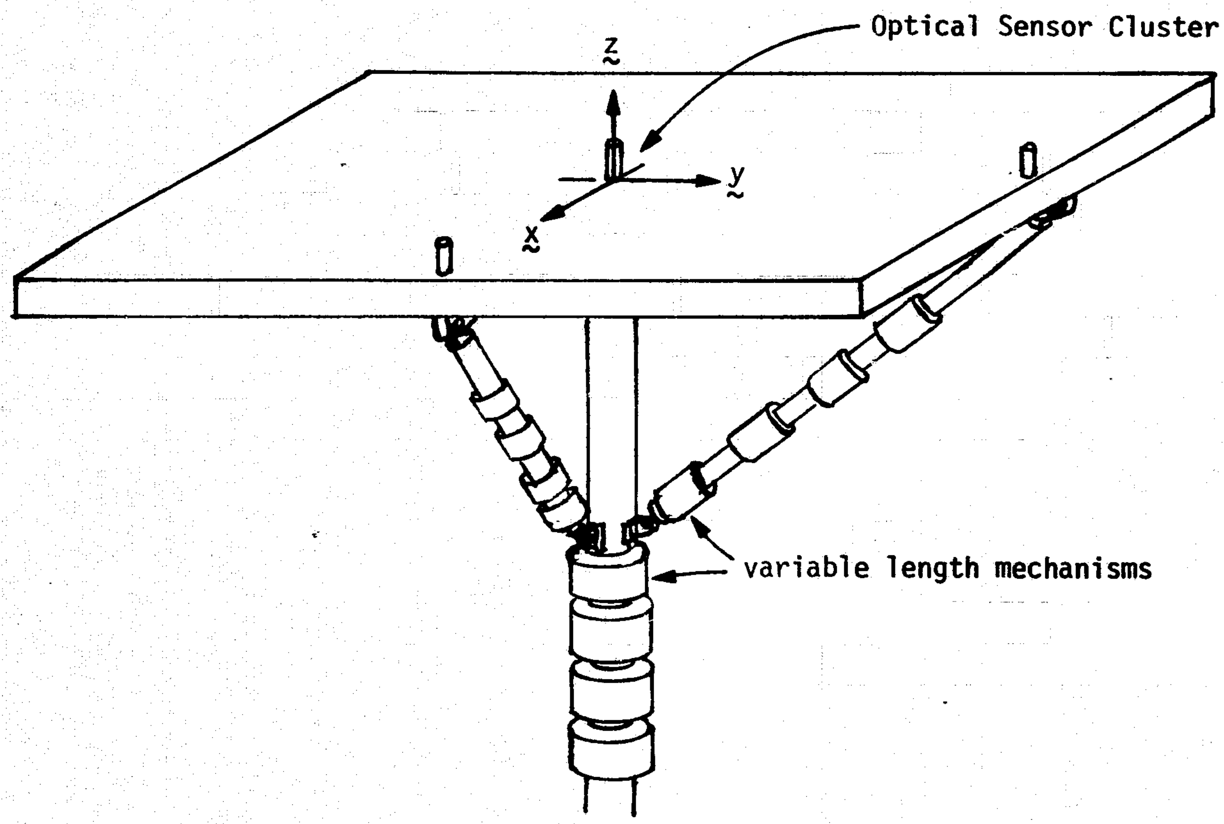

Figure 10. Redundant Variable Length Mechanisms

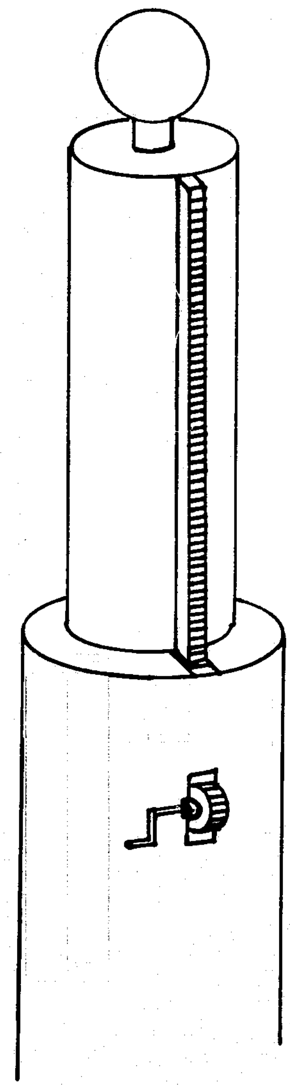

Figure 11. Center Support Strut Manual Adjustment Mechanism

surface contacts necessary to expedite the transfer of thermal energy from the center support strut to the secondary structure. The basic idea of this collet-locking scheme is depicted in Figure 12, where again gears can be employed to provide mechanical advantage since it is assumed an astronaut will be using a rotary wrench to manually crank the collets closed.

The other type of coarse adjustment mechanism connects the attachment points of the azimuth-elevation struts to the subarray. The adjustment is done on the subarray face with a removable crank such that the optical sensors are aligned with the laser reference plane. The mechanism would probably be a simplified version of the variable-length device described earlier, without the electric motor, and includes a locking provision to ensure that it would not work loose. This manual adjustment is required only during assembly so that the dynamic range of the variable-length mechanisms are not needlessly used up in the initial alignment.

5.4 Attainable Flatness

The first requirement imposed on the array is to achieve a high degree of flatness, and a viable technique has been outlined which should be able to attain this flatness over the 1 km distances. The individual subarray tilt specification of 3 arc-minutes random requires that, over the 5m separation between optical sensors, the variable-length mechanism must be able to resolve a vertical distance Δx of 4.4 mm, where Δx is obtained from the relationship

$$\Delta x = 5 \text{ m} \tan [3 \text{ arc-minutes}] = 4.4 \text{ mm } (0.17 \text{ inch}).$$

This accuracy must be achievable for all three optical sensors at the three attachment points of the subarray.

The center support strut is the most difficult to align because it is normal to the laser plane and therefore must directly satisfy this requirement. The feasible number of threads per inch of the worm gear will depend on its diameter, but the resolution can be maintained by high gearing ratios from the stepping motor to the variable-length mechanism. If 10 threads per inch are used, the variable-length mechanism can achieve the center support strut positioning requirement even with some degree of backlash error within one revolution of the worm gear, which is 0.1 inch.

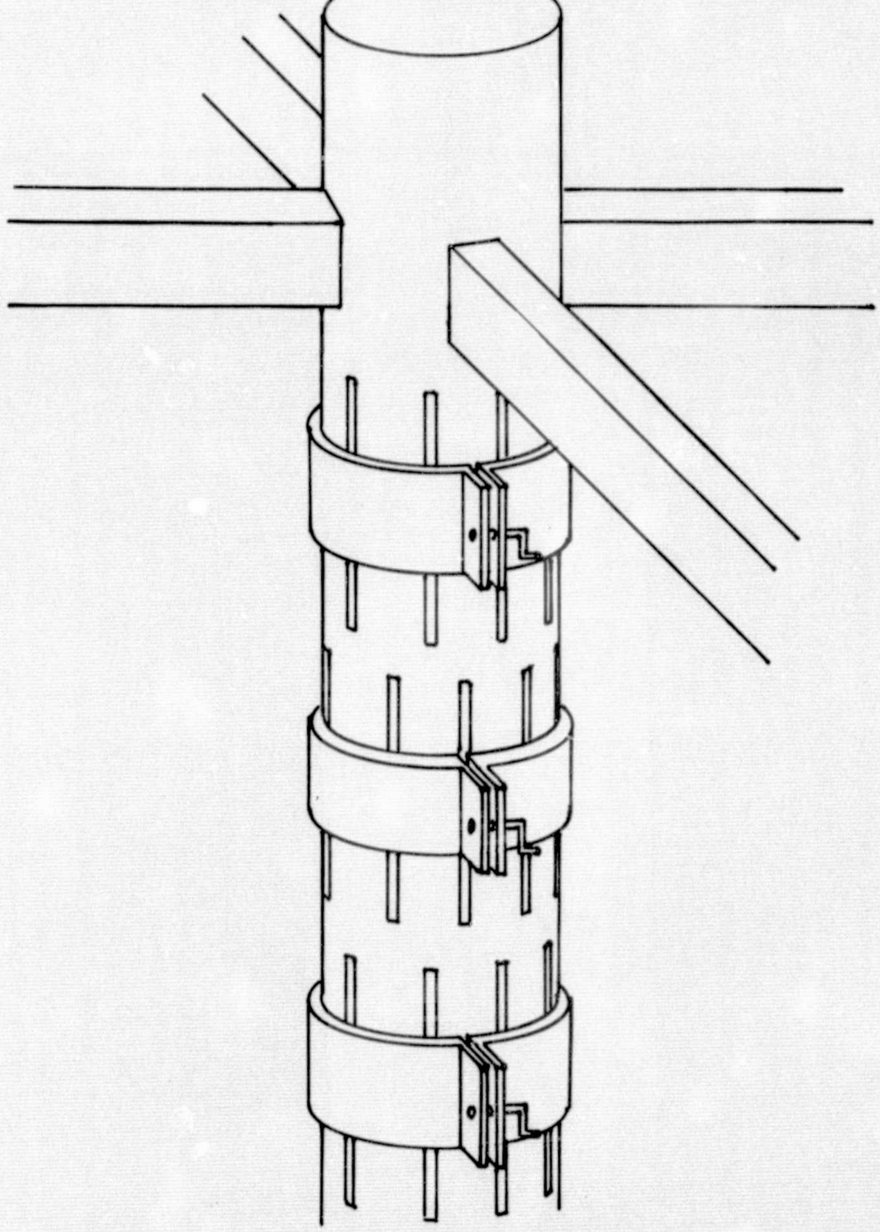

Figure 12. Collet-Type Locking Arrangement for the Tubular Mount

Because of the trigonometric relationship of the azimuth-elevation (Az-El) supports, the achievable flatness specification is simplified. For example, if the worm gear has 10 threads per inch, the subarray is 10 meters wide, and the Az-El support is 3 meters lower than the subarray, each rotation of the worm gear constitutes a vertical deflection of 0.05 inches at the edge of the subarray, as shown in Figure 13. However, because of the gearing ratio from the stepping motor, one worm gear revolution can be divided into many discrete increments according to the mechanical resolution desired. A gear ratio of 10:1 will then permit mechanical control to theoretically 0.01 inch, with the backlash error predominating.

The laser beam has an exit diameter of 1 mm so that, close to the rotating laser beam system, high flatness accuracy is obtained. A high degree of flatness is desired near the center of the array since, with the 10 dB Gaussian illumination taper, most of the radiated power emanates from the central portion. At the extremes of the array, flatness is still achieved, but the tolerances are necessarily greater due to beam broadening and the associated uncertainties related to determining the center of the laser beam. The laser beam is about 3 inches in diameter, but the differential voltage photoconductive sensor locates the center of this beam by balancing the voltages to obtain a null condition. Assuming symmetry of the beam intensity, which can be enhanced by using a beam collimator, and assuming uniformity of photoconductivity of the sensors, which can be verified by spot scanning the sensor in the laboratory, this optical alignment should be able to maintain this flatness to within 0.15 inches over the entire array, extrapolating the specified tolerances used by the manufacturer of the laser system.

5.5 Space-Qualified Electric Motors

The use of electric motor drives in the variable-length mechanisms which point the individual subarrays elicits the question of reliability over a long period of time in a space environment. Although there is no record of extended operation of motors over the period of time expected for the solar power satellite (namely, 30 years), there are a reasonable number of spacecraft using electric motors over a shorter span of time. The Pioneer 10 and 11 spacecrafts, for example, were launched in 1972, and the stepping motors, with relatively low rates of usage, are still

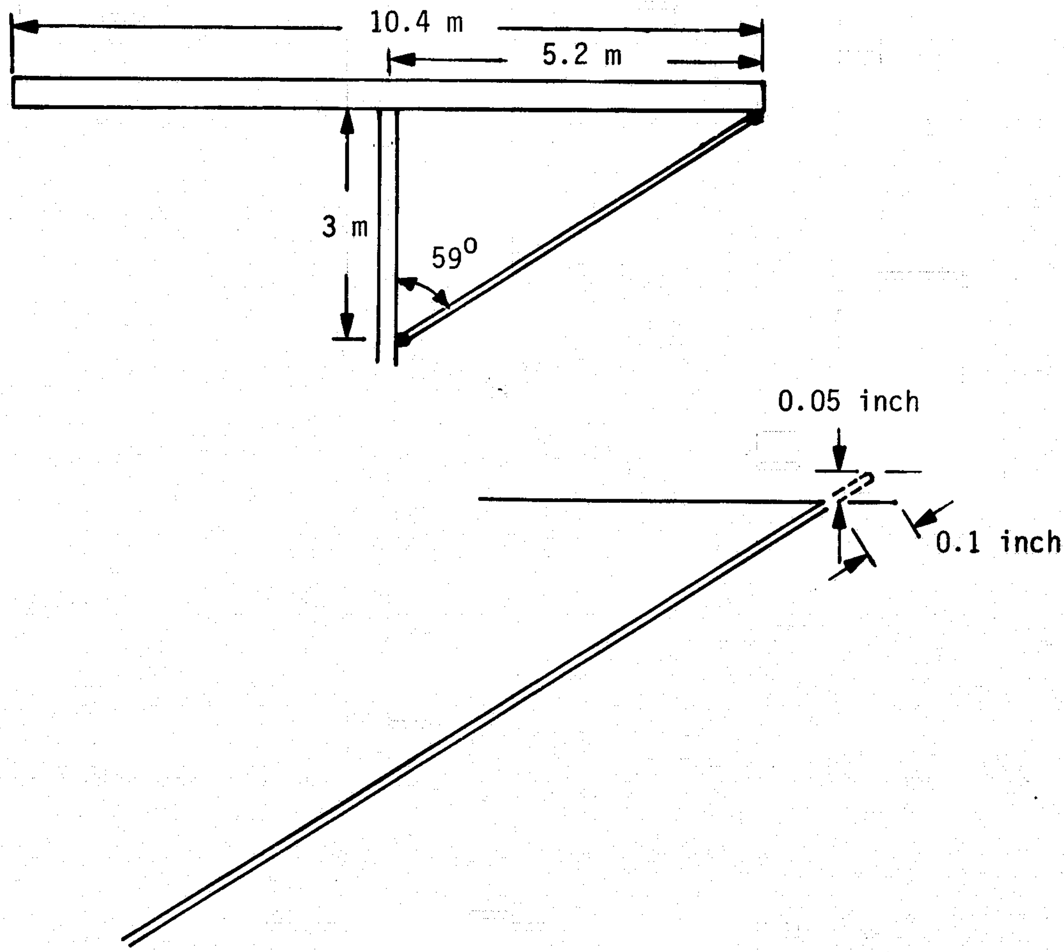

Figure 13. Vertical Movement of Subarray Due to Increase in Variable Length Mechanism

operating satisfactorily. Similarly, no problems have been encountered with the motor used on the shutter of the Landsat Multispectral Scanner launched in 1972. Motors with specifications of a 10-year operating life are now being incorporated into the TDRS gimbal drives. Thus, the SPS design goals are not unreasonable now, even with the redundancy aspects of series-connected variable-length drives.

5.6 Design Recommendations for Extended Motor Life

A discussion with Ernie Schaeffer of Schaeffer Magnetics, a vendor dealing exclusively with space-qualified motors, resulted in some design recommendations which might be considered in implementing high reliability. Low-temperature operation to avoid the outgassing of volatiles in the polymers of the motors would greatly enhance the lifetime. This cold temperature is limited, naturally, by other factors, such as the viscosity of the lubricants used for the proper operation of motors.

Another important factor is the type of lubricants employed. Krytox, for example, is a polymer which is in the "wet" category, and this allows reflow of the lubricant to fill any voids which might arise. Moly disulphide, on the other hand, is a dry lubricant which is considered more stable. Lead is another dry lubricant which the European Space Agency uses.

The possibility of hermetically sealing the lubricating surfaces also serves to increase the operating lifetime of the motors and this feature, although more expensive, would probably be essential or should at least be seriously considered.

6.0 ROTATING LASER BEAM REFERENCE SYSTEM

A commercially available rotating laser system produced by Spectra Physics, Mountain View, California, appears to satisfy many of the requirements for achieving flatness over a very large area. This unit is normally used for leveling in heavy construction applications. Laser beam sensors also are available. The LaserLevel, as the instrument is named, comes in various versions. An automatic self-leveling feature is incorporated, and the unit is hermetically sealed for rugged environments. A picture of the system, describing some of the features, is shown in Figure 14.

The rotating laser beam concept, therefore, is a well-established technique for leveling operations on earth and can readily be adapted for use in space in aligning flat surfaces, which is the case for the MPTS array. Distances of 1000 ft (300 m) on earth are comparable to the 500 m requirement for the MPTS, but no atmospheric turbulances will be encountered in space so that higher accuracies can be attained. Some modifications may be required for this specific application to increase the leveling capabilities such as a collimator to decrease beamwidths at long ranges and increased power outputs. However, this off-the-shelf unit could be used for the MPTS active alignment system with very little degradation in performance.

6.1 Laser Beam Reference Plane

The basic idea is similar to that initially proposed. A rotating laser beam establishes a flat reference plane by sweeping the beam in a circular pattern about the laser axis. A laser is used since it is a phase and frequency coherent light source that maintains a collimated beam at long distances. Collimation is the key to using the laser beam for establishing flatness over large areas since the beamwidth remains relatively small over long distances and therefore a reference plane can be more readily described by rotation. The smaller beam greatly reduces the tolerances to be expected, using averaging methods to determine the beam center.

The choice of the helium-neon laser is a natural one since it is widely used as a scientific measuring tool because it is both reliable and inexpensive. The fundamental wavelength of operation is 6328 angstroms,

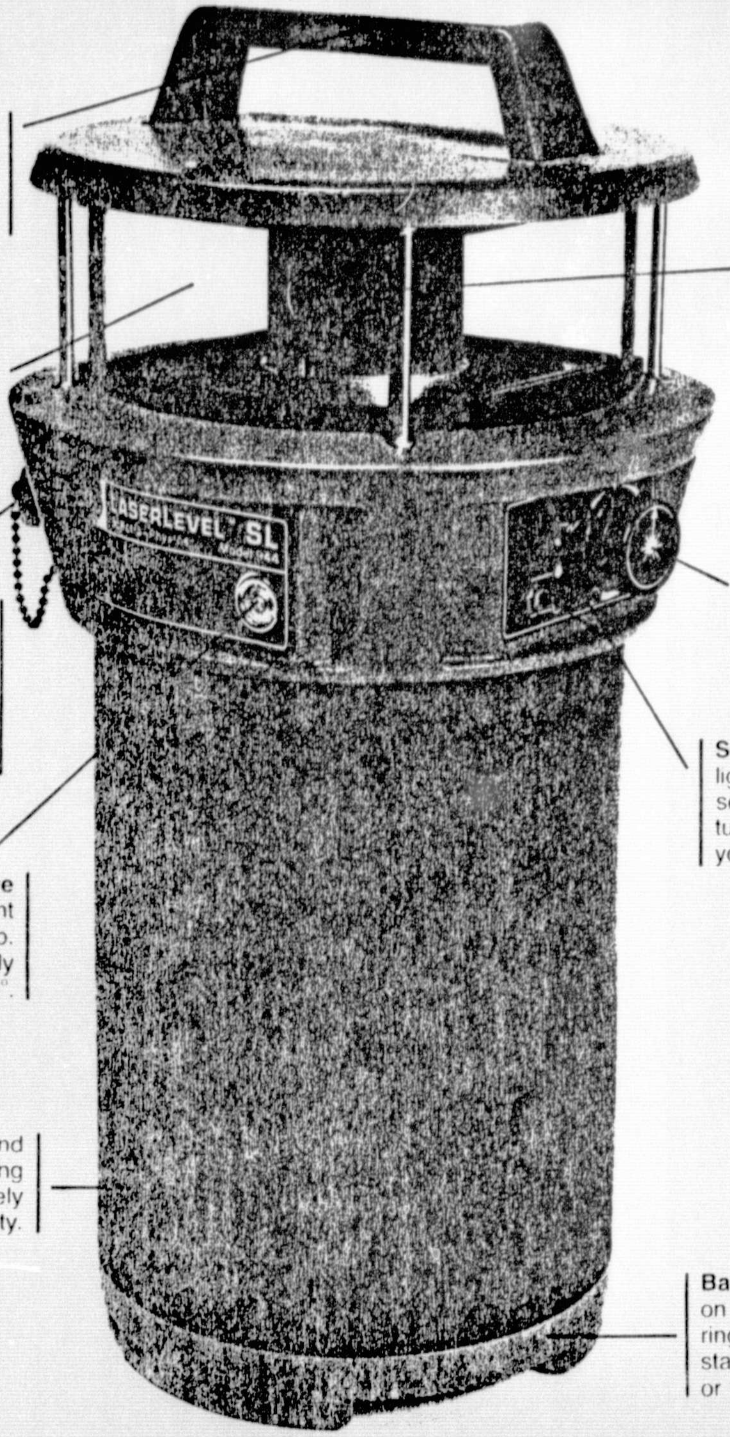

Figure 14. Spectra Physics LevelLaser

which appears red to the human eye, and visual alignment is therefore possible for the assembly operation. Other types of ion lasers with wavelengths close to the peak spectral response of the eye can also be considered since this rotating laser beam technique only requires the collimation inherent to laser beams. Some sophisticated surveying equipment now uses Ga-Al-As solid state laser diodes as a coherent source, but the emitted laser beam is not as collimated as that of the gas lasers and therefore has not been considered for use in the active alignment scheme.

The use of a laser source also permits the use of relatively inexpensive optical detectors. Since at least 21,000 sensors must be used in a three-point subarray support scheme, the number of sensors used is certainly not insignificant. These optical detectors, described in more detail in Section 8.0, operate in a very simple straightforward manner, an important consideration for space programs that demand high reliability.

6.2 Pentaprism Concept

An interesting feature of this rotating laser beam instrument which avoids the mechanical tolerance problem arising from bearings is the use of a pentaprism as the rotating reflector. The pentaprism possesses the unique optical property that a 90-degree reflection occurs even if the prism is tilted moderately. The reason for this behavior is depicted in Figure 15, which shows the two internal self-compensating reflections. A correction wedge is used to make minor adjustments in attaining exact perpendicularity.

The usefulness of the pentaprism can best be illustrated by describing the difficulties of maintaining an exactly perpendicular reflection by mechanical means. An earlier concept used a mirror positioned at a 45° angle rotating about the laser beam axis, as shown in Figure 16. The tolerance problem in maintaining the perpendicularity relied heavily on accurately machined circular flats extending outwards from the laser to provide mechanical leverage and extremely small tolerance bearings good to ± 0.3 mil. Assuming everything was assembled properly, a ± 50 mil tolerance could be extrapolated out to 500 m. Obviously, although this mechanical scheme might be considered possible if it was found that the rotating laser beam plane could not otherwise be implemented, it is cumbersome and expensive to construct and align.

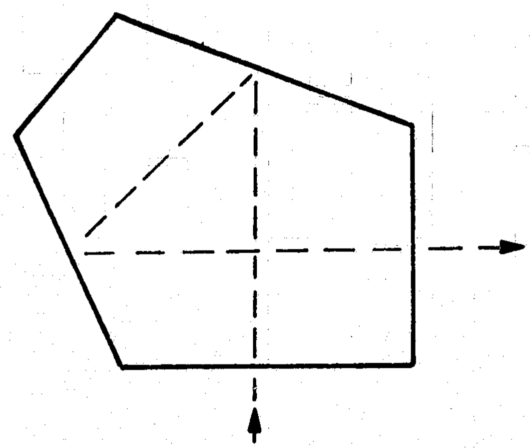

Figure 15. Pentaprism

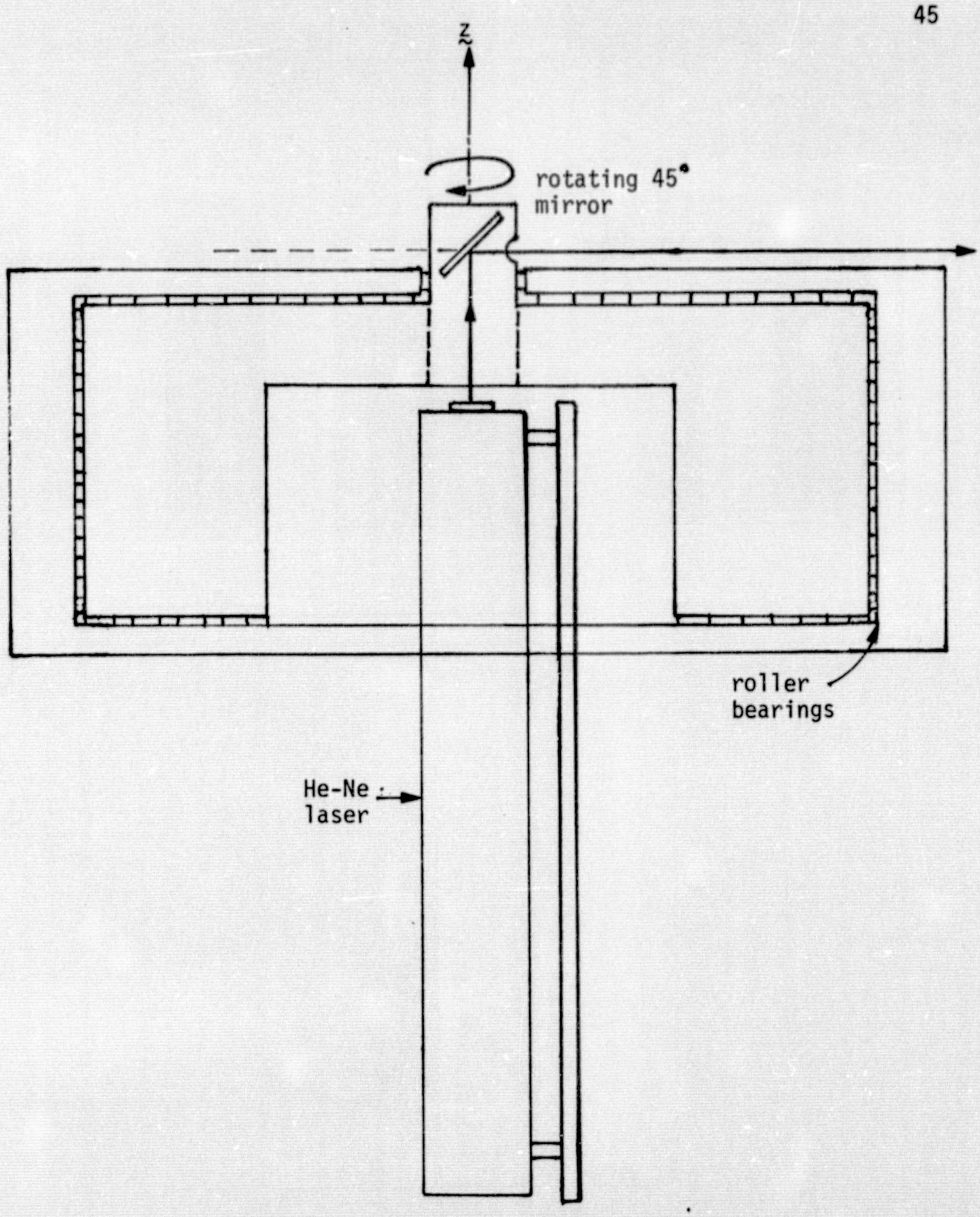

Figure 16. Candidate Rotating Laser Beam Reference System for SPS

The pentaprism already incorporated into the construction-grade equipment has provided a uniquely clever solution to a difficult problem and has thereby greatly enhanced the viability of the rotating laser beam approach to maintaining flatness on the MPTS array.

6.3 Pentaprism Error Compensation Principle

The pentaprism used for the rotating laser beam maintains a perpendicular reflection of the laser beam even under conditions where the rotating laser platform wobbles due to any mechanical misalignments. This characteristic is of inherent importance for large distance alignments such as the 1 km planar array since the mechanical flatness of the array is critical to achieving a high beam efficiency.

The pentaprism is a five-sided prism, shown earlier in Figure 15, that utilizes two internal reflections to produce a net 90° reflection of an incident light beam. Normal incidence of the incoming and exiting beams is used to minimize reflections at the prism surfaces. The two internal reflections are both at 45°, for a total of 90°. The incidence angle θ is defined to be the angle the incident light beam makes with the normal to the reflecting surface. Both internal incidence angles are therefore 22.5°. The exit beam is thus perpendicular to the incident beam.

The pentaprism error compensation principle for vertical tilting will be demonstrated by describing the optical path through the prism for a tilt of 2.5°, a rather moderate tilt which, if introduced in the case of the earlier mechanical system, would have prevented flatness from being attained.

6.3.1 Vertical Tilting

A simple analysis of the pentaprism optical principles is outlined to demonstrate the self-compensating feature resulting from two internal reflections. In addition, in order to establish a feeling for the possible errors involved, a 2.5° tilt error is introduced to determine the impact of the misalignments that can be tolerated.

If a mechanical tilt is now introduced, it will be shown that this perpendicularity is maintained. Suppose the prism is tilted by 2.5°, as depicted in Figure 17. It is now essential to incorporate the effects of Snell's law since a slight angular displacement occurs.

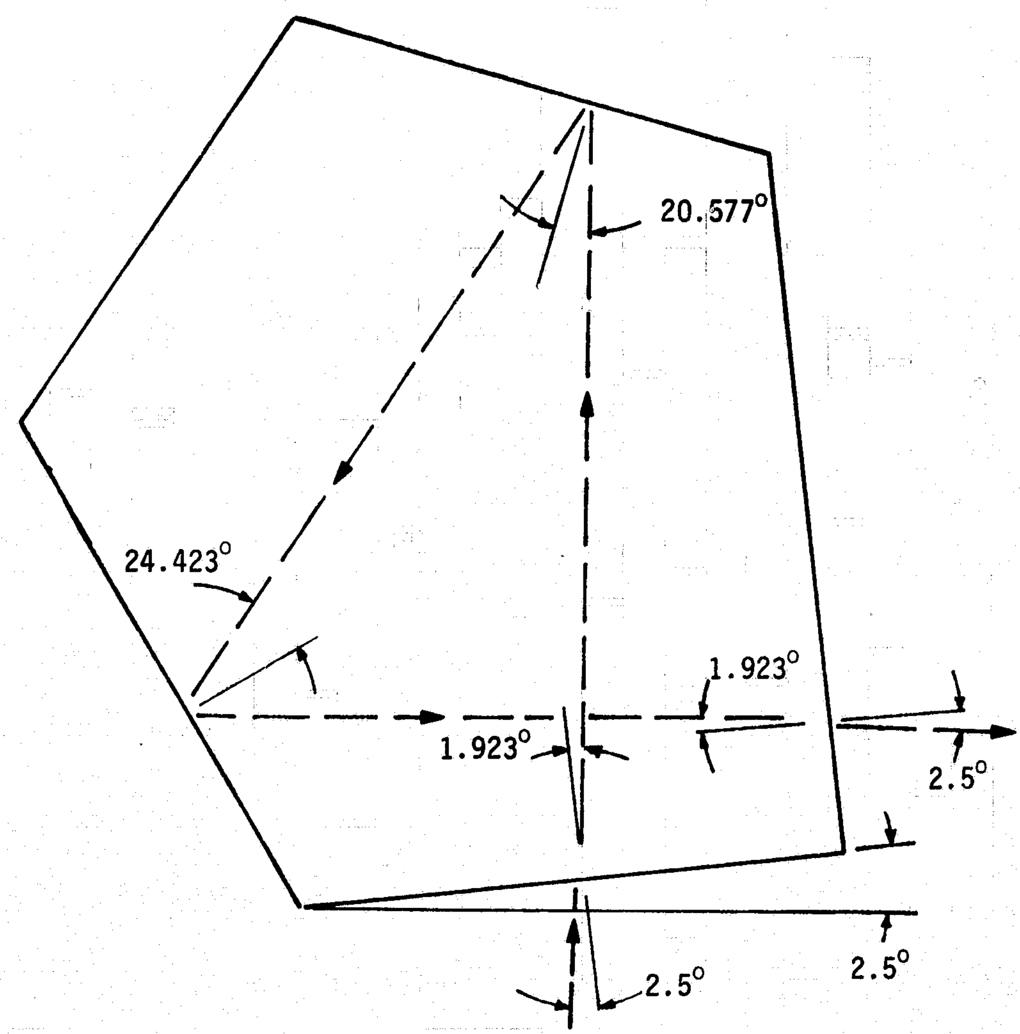

Figure 17. Angular Relationships of the Tilted Pentaprism

Snell's law is given by the relationship

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where n is the refractive index. Figure 18 shows the respective incident and refracted beams.

If the index of refraction of the prism is taken as 1.3, then the first refracted angle is

$$\theta_2 = \sin^{-1}\left[\frac{n_1}{n_2}\sin \theta_1\right]$$

$$= \sin^{-1}\left[\frac{\sin 2.5°}{1.3}\right]$$

$$= 1.923°$$

This angular deviation results in an incident angle for the first reflection of 22.5° - 1.923° = 20.577° and is similarly reflected at that angle. At the second reflection, the incident angle is 22.5° + 1.923° = 24.423°, with an identical reflection angle. The reflected beam is then incident on the exiting prism surface at 1.923° from the normal and subsequently is refracted (again by Snell's law in reverse) to be 2.5° from the normal, which maintains perpendicularity.

The "cost" of this self-compensating reflection feature of the pentaprism is a slight displacement of the position of the reference plane, as shown in Figure 19. This displacement is a direct function of the size of the pentaprism and the location of the tilting axis. The smallest displacements arise from the smaller prisms tilting at the center. It is obvious, however, that these displacements are negligible compared to the beam diameter and therefore need not be considered at the extreme edges of the array where beam broadening effects are the predominant sources of error.

6.3.2 Horizontal Tilting

The self-compensating multiple reflection feature of the pentaprism holds only for the vertical tilting case described previously. The complementary case, horizontal tilting, is not very interesting but the effects of such tilting will be described in terms of the overall ability to

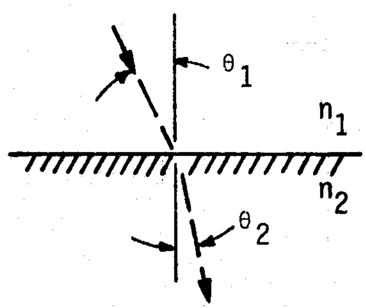

Figure 18. Refraction Angle

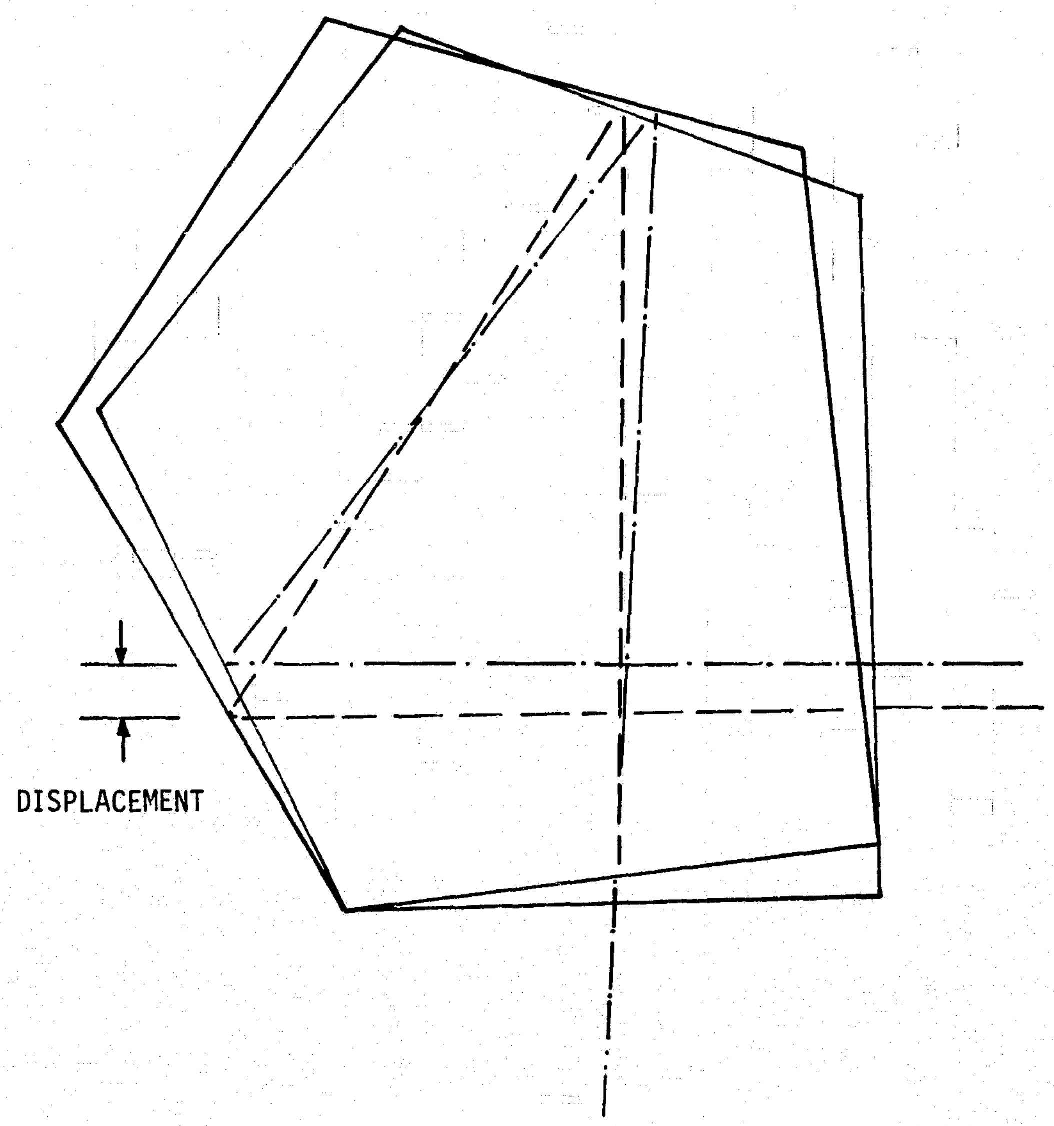

Figure 19. Exaggerated Displacement Due to Tilting

describe a flat laser beam reference plane.

If the tilt in the pentaprism occurs in the orthogonal direction and tilts with its axis parallel to the exit beam, the optical path is as shown in Figure 20. The main effect arises from Snell's law since normal incidence does not occur at the first surface of the pentaprism, denoted as (a). As a result, although the refracted beam is bent towards the normal to the pentaprism first surface, the second (b) and third (c) reflections which were self-compensating for the case of vertical tilting retain this angular deviation from normal and the beam exits the pentaprism at point (d), which is displaced from the vertical laser beam axis. As was explained in the vertical tilt case, this displacement is a function of the size of the pentaprism and the amount of horizontal tilt.

The net result, however, is a beam that is not perpendicular to the laser axis but is tilted upwards at the same angle as the horizontal tilt. The analysis utilizes the self-compensation of the multiple reflections in the vertical direction and simply employs Snell's laws of refraction at the boundaries. By the symmetry conditions imposed by the two internal reflections, the displacement occurs and the exit beam is parallel to the plane of the first pentaprism surface which is, by definition, tilted and therefore perpendicularity is lost. Although this case is somewhat exaggerated, it does indicate that special care must be taken to exactly align the pentaprism for operation at extreme ranges.

The compensation technique to correct this misalignment would be exactly the same as for the vertical tilting case where a correction wedge, made of the same material as the pentaprism, is inserted at the exit face of the pentaprism. The angular relationship of the exiting laser beam is affected by the angle and thickness of the wedge. For the case of the horizontal tilt, the wedge is rotated a corresponding amount in the opposite direction to regain perpendicularity and, since the degree of tilt in both orientations are by design small, the correction wedge properly placed can rectify misalignments.

6.4 <u>Laser Beam Broadening</u>

The most deleterious characteristic of the laser beam reference system is beam broadening, the tendency of a laser beam to gradually increase with distance due to the lack of precise collimation. Even

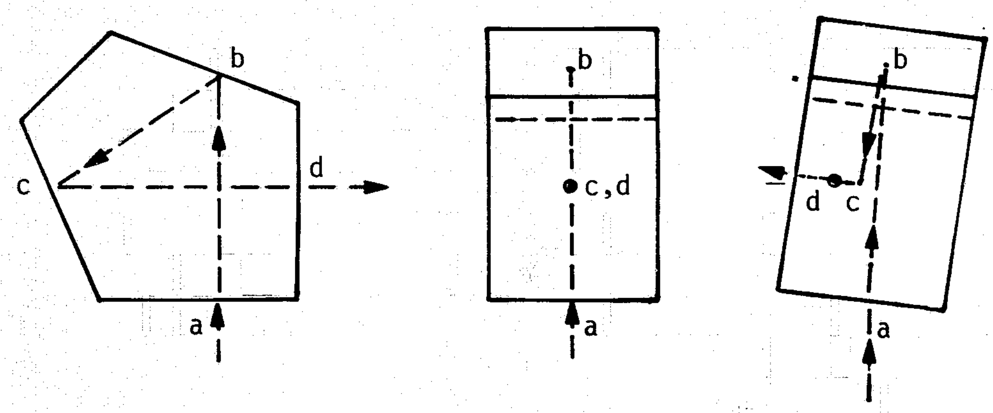

Figure 20. Horizontal Tilting of the Pentaprism

though laser beams are noted for their relatively narrow beams, at long distances this beam broadening can create problems, as is the case for the laser beam active alignment system proposed here which has optical sensors located 500 m away. At best, using careful collimation techniques, the laser beam using existing systems could be as large as three inches in diameter at extreme ranges. The active alignment system should be designed to operate properly with the 3-inch diameter beam, but higher alignment accuracies will result if the smaller beam diameters can be achieved so that some further development effort would be warranted.

6.4.1 Beam Divergence Relationship

The beam divergence with respect to exit beam diameter and distance for the helium-neon laser has been experimentally determined to behave in a manner which can be described by the relationship

$$d = d_0 \left[1 + 6.492 \times 10^{-9} \frac{D^2}{d_0^4} \right]^{1/2}$$

where d is the laser beam diameter (cm), D is the distance (cm) and d_0 is the laser exit beam diameter (cm). For example, with a typical exit beam diameter of 1 mm and a distance of 500 m (1625 ft), the beam diameter is

$$d = (0.1) \left[1 + 6.492 \times 10^{-9} \frac{(5\text{x}10^{-4}\text{cm})^2}{(0.1)^4} \right]^{1/2}$$

$$d = 40.29 \text{ cm } (15.86 \text{ in}).$$

The calculations indicate that a simple helium-neon system will not suffice since the beam is much too broad for accurate alignment. Special techniques, then, are required to improve the collimation of the laser beam.

It should be noted that the beamwidths at 500 m should be extensively evaluated by testing since the available data is extrapolated and many of the manufacturer's specifications are not oriented to applications beyond 1000 ft.

6.4.2 Collimator Principles

A collimator is used to ensure that the beam width remains small at long distances. By using special optics and spatial filters, spurious

modes which cause beam divergence are removed from the laser beam. The net result is that the exit beam is approximately 5/8 inch in diameter and increases to a little over an inch at 1000 ft. Since the array is 1 km wide, the laser beam diameter can be extrapolated to be about 3 inches at 500 m.

A plot of the expected performance of the laser beamwidth with range is shown in Figure 21 for both cases, with and without a collimator, to compare the improvement in reduced beamwidths at extreme ranges.

The basic description of collimation involves focusing, spatial filtering and collimation. Similar methods are commonly used for beam expanders where the beam is reconstructed to have a larger diameter during collimation by using optics with longer focal lengths. The spatial filtering removes much of the harmonic and spurious modes always present in a laser discharge by utilizing the Fourier transform resulting from the focusing optics. An appropriately sized pinhole permits only the transmission of the dominant laser mode and physically blocks out the other components so that the resultant collimated beam is "pure." Some power output loss is normally associated with this process, but higher power helium-neon lasers are readily available.

6.5 Initial Rotating Laser System Alignment

The alignment of the laser rotating system governs the placement of the edge subarrays since the laser establishes the flatness criteria for the array. Since the subarray support systems have limited range, the rotating laser system must be initially aligned to position the edges of the subarray within reasonable distances of the secondary structure. The subarrays will have been previously installed in temporary positions within the tubular mounts in the secondary structure during the construction phase. Due to the flexibility of the single support strut concept, the subarrays would be neatly stowed adjacent to the secondary structure and need only be manually cranked into position during the individual subarray alignments. This feature allows the rotating laser plane to be positioned to intersect three special initial alignment sensors at the edges of the secondary structure. These three optical sensors would be located at the desired corridor height above the secondary structure and the optical reponses will be monitored to indicate coincidence of the laser beam on the sensor.

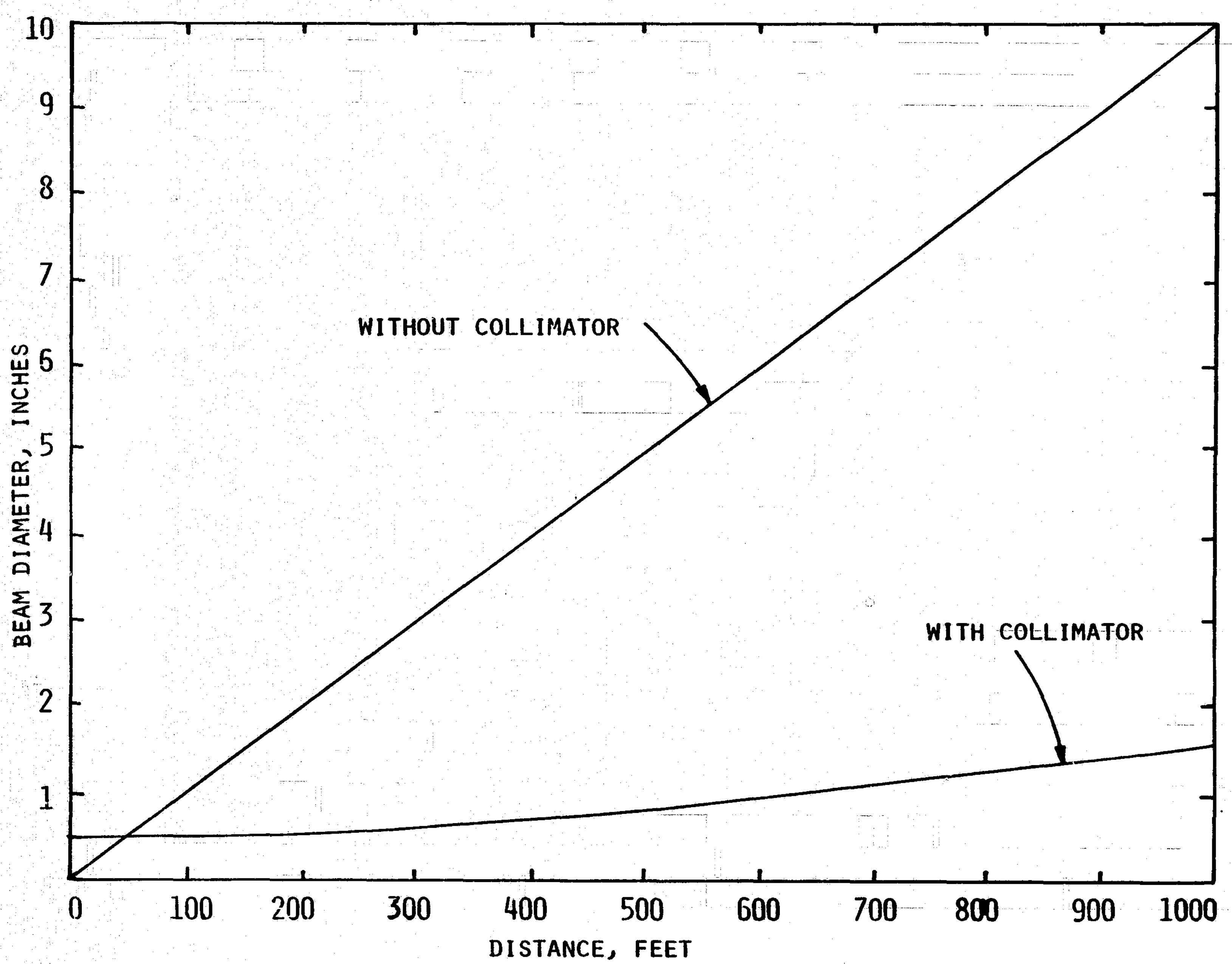

Figure 21. Beam Divergence (With and Without Collimator)

The same type of three-point mounting scheme can be used to support the rotating laser beam system, with the azimuth-elevation adjustments being manually operated. First the height of the rotating laser beam system is adjusted to the approximately desired corridor height, the same height as special alignment sensors. The azimuth-elevation tilting struts are then adjusted to align the laser beam with two of the sensors. And finally, using iterative techniques, the height of the rotating laser beam system is adjusted until all three sensors are aligned with the laser beam plane. High accuracy is not required at this time since it is a very preliminary alignment to initially set the array reference plane with respect to the secondary structure.

There are various approaches that may be taken for this initial alignment since it is only done once. For example, the initial alignment may be accomplished by visual observation, by locating astronauts at the three sensor positions and having them communicate by radio as to the position of the laser beam incidence on a measuring rod mounted above the secondary structure. Another approach is to employ the special alignment sensors mentioned previously, which can also serve as alignment checks which might be periodically used to verify the position of the array on the secondary structure.

These special alignment sensors will have to be different than the other optical sensors in that a wider latitude of height will have to be tracked. The existing laser rod detector can possibly be adapted for this role since it has a dynamic range of 5.5 feet at ranges of 1000 ft. An optical sensor moves up and down the measuring rod and takes 16 readings of the laser beam to determine the beam center. If this information can be transmitted to the rotating laser beam system, the proper adjustments can be readily made, and the results of the adjustment would be immediately known. The motor drive controlling the movements of the optical sensor and the measurement system itself would have to be modified.

Another technique might use a linear array of sensors such as photodiodes positioned periodically on the measuring rod. The illumination by the laser beam of a group of sensors would indicate position, and the signals could be sequenced by means of a shift register and transmitted to the laser plane alignment group.

6.6 Optimal Positioning of the Rotating Laser System

The optimal location of the rotating laser beam system satisfies two conditions. The first is that a minimal number of rotating laser systems is desired. The second is that all optical sensors must be visible from the rotating laser axis. The limitation of laser beam broadening requires that the rotating laser beam system be centrally located on the array. The clearest field of view is on top of the planar array and, therefore, the location of the optical sensors on top of the array has been chosen.

Having undergone the analysis to this point, it is now essential to determine the key design parameters on which to base the optimum location of the rotating laser system. First, it appears that the rotating laser system is best positioned near the center of two service corridor intersections. In this manner, the closest sensors are located at the centers of the four adjacent subarrays, as shown in Figure 22. These sensors constitute the largest optical blockages, with subsequent sensors located periodically every array diagonal (14 m) behind it. In order to avoid the blockage of the next optical sensor, the rotating laser system has to be offset at least a blockage sector angle ϕ away. By an approximate reciprocity concept, this only requires an offset of 0.25 inch from the center of symmetry. It is important to note that this blockage is greatest at the nearest sensors and that subsequent farther sensors have smaller blockage cross-sections and thus intrinsically satisfy the clear-view criterion.

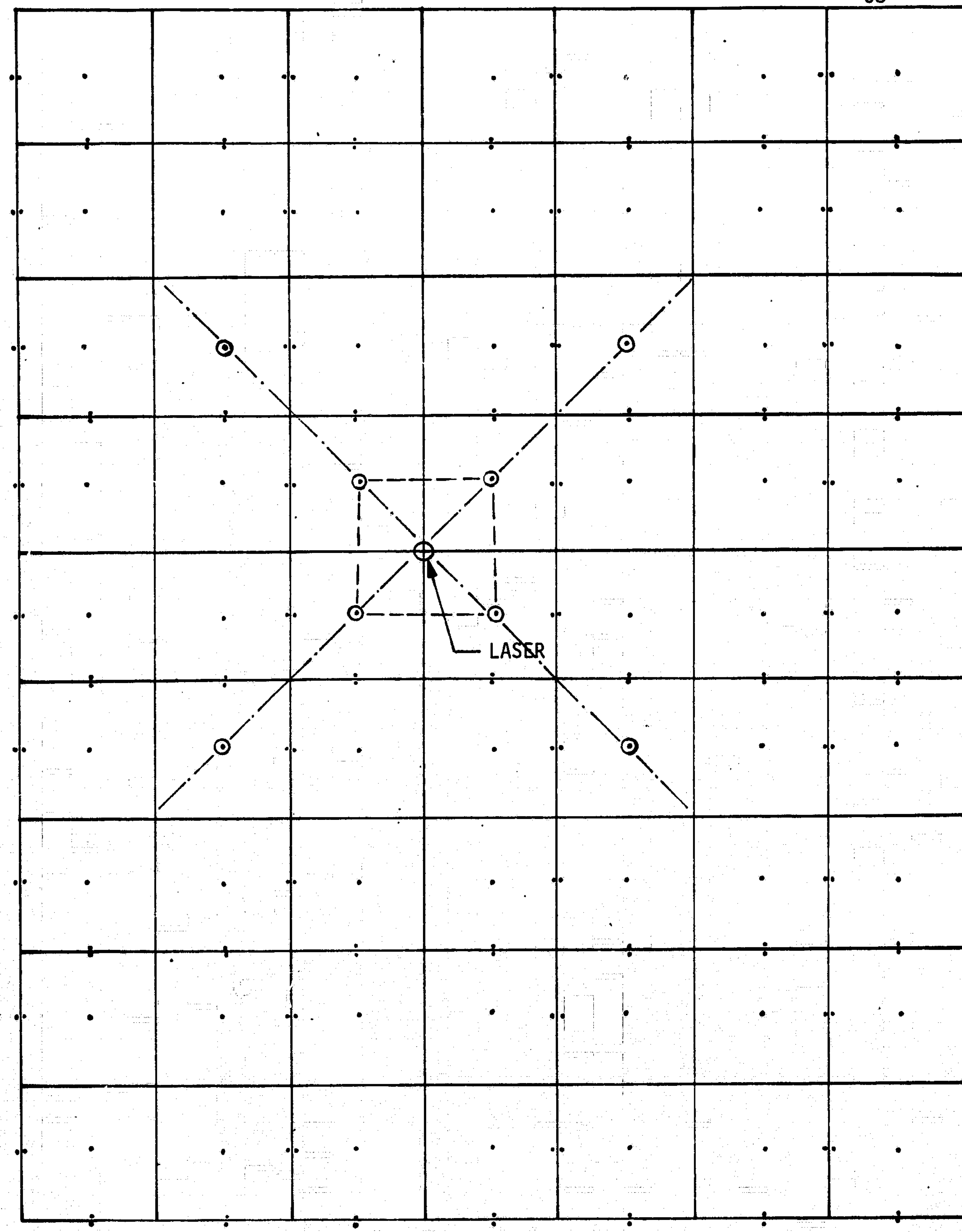

Figure 22. Location of Rotating Laser System and Nearest Optical Sensors

7.0 BLOCKAGE EFFECTS

The laser beam reference plane for the active alignment scheme has been located on the face of the array to minimize blockage effects. During an earlier phase of the study, multiple laser planes were located beneath the subarrays because of the possibility of interactions between the radiated power and the optical sensors which would affect the overall beam efficiency. The disadvantage of this method was that more than one laser reference was necessary due to blockage by the support struts, which also created a problem with coincident alignment between the two or more laser planes. The alternative was to find a compromise and, as a result of an analysis of a dipole on the array face discussed in Section 10.0, a tractable solution to the optical sensor on the array face was determined such that blockage is minimized and only one operating laser system is required.

7.1 Sensor Location

The optimum locations for the optical sensors are directly above the attachments of the azimuth and elevation struts at the edges of the subarray and above the ball joint at the center. The reason for locating the sensors at these positions is that the adjustments resulting from the variable-length mechanisms are mechanically related to these points. If the azimuth sensor, for example, indicates misalignment, the appropriate variable-length mechanism simply rotates about this ball joint until alignment occurs, and this movement is essentially independent of the elevation control. In order to make the control movements independent of the orthogonal control movements, the sensor must be located on the imaginary line between the ball joint and the respective attachment point. That line constitutes the rotational axis for the orthogonal control, and a similar relationship holds for the other tilting axis. Thus, the two tilt controls are decoupled from each other.

The location of the sensor at the edges of the subarray provides some mechanical leverage to the tilt control and thus increases the pointing accuracy. The distance between the sensors is at least 5 m apart such that a vertical deviation of 0.17 inch at the attachment point must be detected to maintain the subarray random tilt specification below 3 arc-minutes. Theoretically, the optical sensors would be better if

they extended outward from the edges but, on a practical basis, with the relatively tight packing of the subarrays, the performance gain is not justified.

One convenience that might be incorporated would be the ability to laterally move the sensor to ensure a clear field of view to the rotating laser beam. This lateral movement would only need to be of the order of two to three optical sensor widths to avoid blockage. Since the exact position of the sensor is not critical, a slotted aperture on the array face would permit an astronaut to move the sensor if it was found that total or partial blockage was evident during the assembly process.

Another method which minimizes the effects of blockage would be the use of a cluster of optical sensors at each attachment point since each sensor operates independently and therefore reduces the chance that an inadvertent blockage would disrupt active alignment.

7.2 Blockage "Cells"

Since so many subarrays exist, the concept of blockage cells has been conceived to attempt to simplify the understanding required to avoid optically blocking other optical sensors located farther away. This blockage cell concept centers on the position of the rotating laser beam system and uses the symmetry of the optical sensors with respect to service corridors. Since the array is laid out in a square matrix of subarrays, the closest sensors, if the rotating laser system is located at the center of the intersection of two corridors, are located at diagonals as indicated in Figure 22. The next diagonal sensors located behind the closest ones are in the next cell, and these sensors are likewise circled for clarification purposes. The basis for using symmetry is to slightly offset the position of the laser beam source to offset the position of the farther sensor so that, in effect, a line of diagonal sensors is seen by the laser. The direction of offset will probably be along a subarray edge, but the actual location would be a candidate for more analysis and only the feasibility of the blockage cell concept is justified here.

The next blockage cell is sketched in Figure 23, where groupings of adjacent azimuth and elevation sensors are circled. The respective farther cell, with related groupings of sensors, is also indicated to show the symmetrical relationship that evolves. The same laser beam source

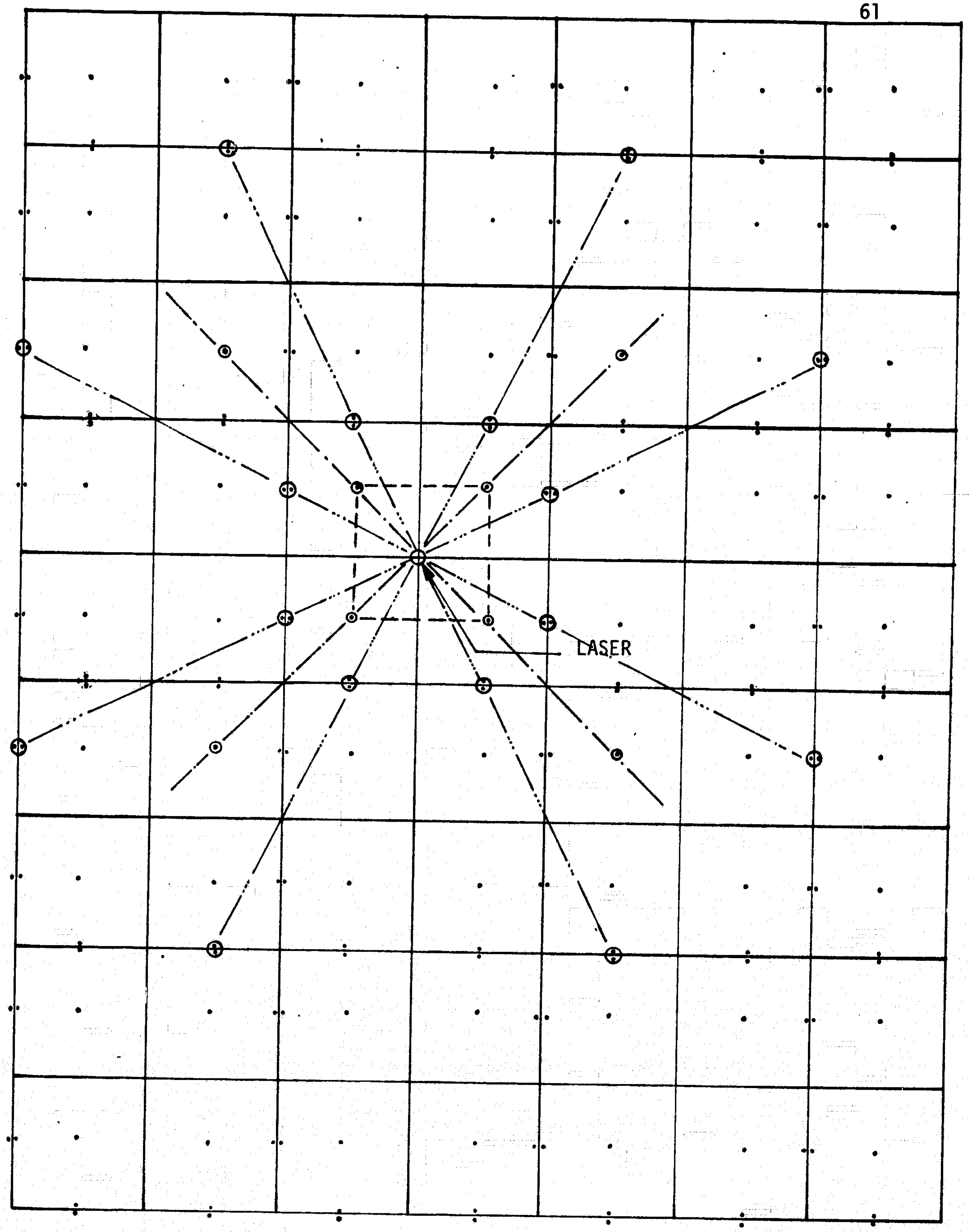

Figure 23. Location of Rotating Laser System and the Two Nearest Sets of Optical Sensors

offset used for the first blockage cell will also cause these groupings to appear offset in a line to the laser and, therefore, all groupings will be visible.

Using this concept, the closest cells are most important since the closer optical sensors subtend a larger blockage sector than subsequent further sensors. For example, a sensor that is twice as far from the laser subtends half the angle of the one closer in. Therefore, greater emphasis is placed on the nearest blockage cells and, by extension of this argument, all optical sensors should be visible from one offset centrally located position.

7.3 Sensor Blockage Cross-Section

The existing laser sensors used for construction are contained in packages about 2 inches wide and about 3 inches high, excluding the associated biasing circuitry which can be located at other convenient positions. In practice, these sensors can be made much thinner, about 0.25 inches wide, to reduce optical blockage.

Utilizing the symmetry of the subarrays, the two-dimensional layout of the arrays would place the rotating laser at a position offset from the exact center to utilize the displacement of adjacent sensors lined up in a radially symmetric manner. The center of symmetry is taken in an area where few optical sensors are located. This is to reduce the effects of optical blockage since the ones nearest the center, being closer, have a larger blockage cross-section. For example, if the optical sensor is 0.25 inches wide, then the effective blockage angle ϕ is

$$\phi = 2 \times \tan^{-1}\left(\frac{0.125 \text{ inch} \times 0.0254 \text{ m/inch}}{7.07 \text{ m}}\right) = 0.0515°$$

for a 10 m wide subarray.

Optical sensors located at farther distances subtend even smaller angles and are thus less susceptible to being blocked by closer sensors. Using the example shown earlier in Figure 22, the second set of diagonal sensors, being three times farther away, would have a corresponding blockage angle of one-third that of the first set of sensors calculated above.

The second optical blockage cell was shown in Figure 23, where two sensors are located at a distance of 11.2 m away. The 0.25 inch wide sensor blocks an angle of 0.0325°, and the next sensor can again be seen by

an offset of 0.25 inches from the center of symmetry. Thus, it appears that these thin sensors, combined with the long distances between sensors, make this technique viable using only one rotating laser system.

7.4 Redundant Sensors

Redundancy can be implemented for the optical sensors since they can be made very thin. It would not be unreasonable to use two or more optical sensors with each variable-length strut, with each controlling a separate variable-length mechanism positioned in series along the strut. Any one of them can then adequately align the subarray if optical blockage did occur, although the possibility is quite remote if the sensors are positioned after installation.

The cluster concept mentioned earlier uses a grouping of redundant sensors above the attachment point. The blockage angle will increase, however, since the sensors will have a larger effective cross-section. Therefore, the amount of offset of the rotating laser system from the center of symmetry will have to be correspondingly increased. Because of the symmetry concept, it probably is not a wise idea to intersperse the sensors in the cluster such that farther sensors might be blocked. Instead, the grouping should consist of adjacent sensors aligned normal to the laser beam. In this manner, the blockage cell concept discussed previously will remain valid.

7.5 Redundant Rotating Laser Systems on a Common Baseplate

The use of redundant rotating laser beams to increase reliability requires additional laser systems which will either operate in the event of a system failure or will operate simultaneously to compensate for any drastic environmental change such as a solar eclipse. Probably the most practical approach during normal operation is to use only one laser system since the mutual alignment of more than one system would be too complex. Minor misalignments between redundant laser planes are acceptable if only one is used as a reference at any given time.

The use of a common baseplate simplifies the initial alignment procedure of the previous section since the laser planes of the redundant systems will be essentially coincident by design.

In order to maximize efficiency, one might use the "unused" sectors

subtended by the existence of the service corridors which are 10 m wide and 500 m long. If the open sector, ϕ', is $[2 \times \tan^{-1}(5m/500m)] = 1.14°$ wide and the rotating pentaprism is 2 cm wide, then two rotating laser systems can be placed symmetrically 0.5 m from the center of symmetry, or 1 m apart, without interference. Similarly, three or more aligned lasers 1 m apart along the center of one of the intersecting corridors satisfy this minimal blockage requirement. Note that only one of these lasers need be operating to satisfy the flatness alignment scheme.

8.0 OPTICAL SENSORS

The optical sensors are the electronic means of detecting the laser beam reference and aligning the subarray by centering the beam on the sensor elements. Being essential to the active alignment scheme, special design considerations must be taken into account since at least 21,000 of these sensors perform the alignment. Because of laser beam broadening, these sensors have to operate with a laser beam width of at least 3 inches at the extremes of the array. Directional information must be provided to the motor drives to indicate the direction of motion required. Precise alignment is very important close to the center of the array and should be maintained even to the extremes of the array. And finally, if possible, the sensors should be very reliable, readily replaceable, relatively inexpensive, incorporate some converging optics to maximize signals, and possess some optical filtering capabilities to exclude background illumination.

8.1 Types of Optical Sensors

There are two basic categories of optical sensors being considered for this active alignment application. Photodiodes are localized sensors that indicate incident light by generating a voltage signal across the two leads. The laser light detector used in conjunction with the rotating laser beam system for construction applications uses three photodiodes to sense the laser beam. The center one indicates alignment and the outer two indicate the direction required to realign the beam. Photoconductors are made of semiconductor material which changes resistivity when illuminated and therefore must be externally biased. An optical sensor design is proposed for this active alignment scheme using this photoconductivity principle and will be discussed in more detail in a later section.

8.1.1 Photodiodes

Photodiodes are junction devices that develop increased reverse saturation (i.e., leakage) currents when illuminated by the optical excitation of free charge carriers in the active intrinsic region of the diode. The designs facilitate maximum illumination by spreading the junction over a larger area, increasing the sensitivity of the detector

since each incident photon with the proper energy generates current carriers. Since the skin depth is small, most of the excitation occurs close to the junction surface. Some versions use very small junction areas to define physical resolution and, at close ranges, these small junction area diodes would be used to determine beam center. At extreme ranges, however, the diameter of the laser beam limits the accuracy of the flatness alignment. Beam centering techniques, however, increase this accuracy. The Spectra Physics method mechanically moves the sensors and takes many measurements, thereby establishing a mean value which determines the beam center. This method is appropriate for earth applications with atmospheric turbulence. Another technique might use an array of photodiode sensors to determine the beam center.

The commonly used intrinsic semiconductor material for photodiodes is silicon. Gallium-arsenide (GaAs) is also sometimes used but, being a compound semiconductor, is more exotic. The same technology that is involved in the solar cell development is applicable here since the solar cells are photodiodes. The effects of radiation on photodiodes do create some problems for the long lifetime operation of the MPTS, but it has been shown that radiation causes less degradation in performance with GaAs and, being superior in conversion efficiency, is a logical candidate if photodiodes are seriously considered for this use.

8.1.2 Photoconductors

There are two types of photoconductive semiconductors. One type includes the intrinsic high resistivity semiconductor materials such as silicon, indium antimonide and mercury or copper doped germanium. These semiconductors are fabricated by photolithography and etching techniques into thin rods that become the sensor elements. These elements are very small, of the order of 0.1 inches, and are extensively used in laser and infrared systems for target seekers in military applications. Another class of photoconductors is fabricated by vacuum deposition or liquid growth. These photoconductors include cadmium sulphide, lead sulphide, and lead-tin-telluride. Although related in nature, most of these photoconductors are prepared using special formulations and oxidation processes which control the photoconductive properties. Although the exact photoconductive mechanism is not well understood, it is postulated that the

granular nature of the depositions and the importance of oxidation results in a multiple p-n junction effect which results in a high dark resistivity. For the proposed photoconductive sensors, the class of deposited photoconductors is recommended because they more readily suit the sensor element size requirement and their spectral response curves more closely match the helium-neon laser.

8.2 Photoconductor Design Parameters

The first criterion, once the class of deposited photoconductive semiconductors is selected, is the specification of the detectivity of the proposed sensor for the optical source used. In this particular case, the photoconductor must be sensitive for the dominant wavelength of the helium-neon laser, 6328 angstroms. Second, the desired dark resistance must be determined to evaluate the circuit constraints, such as the voltage signal of the incident optical signal and continuous biasing power requirements. The proposed configuration, being two colinear elements about 5 inches in total length, also must be considered in analyzing the thickness and width of the photoconductive sensor element. Long-term reliable operation must also be considered since the outgassing of certain volatiles may upset the required stochiometric composition and therefore require protective film overlays. The effects of radiation on this type of device should be investigated although, being amorphous, it theoretically would cause negligible changes in performance, unlike the case of well-defined diode junctions.

The actual proposed design of the optical sensor, discussed in detail in the following section, incorporates many of these design parameters into a nulling-bridge sensor which is capable of selectively detecting the laser beam over the entire range up to 500 m while maintaining alignment accuracy with an inherent beam centering technique.

9.0 PHOTOCONDUCTIVE SENSOR DESIGN

The photoconductive sensor is used with the rotating laser beam system to achieve flatness over the large microwave planar array. A preliminary design which has attempted to include many of the necessary features for satisfactory operation has evolved during the course of this study and will be used as an example for descriptive purposes.

9.1 Physical Description

A sketch of the proposed sensor design is shown in Figure 24. This particular configuration is adapted for the nulling resistive bridge-type of motor drive in order to establish a consistent alignment plane, which is defined by the gap between the two sensor elements. The size of the photoconductive sensor elements is determined by the maximum distance from the rotating laser system as a result of beam spreading. The overall length of each sensor element for a distance of 500 m should be of the order of 2.5 inches, with two colinear elements composing the sensor. The 5-inch total length of the sensor can also be used as a visual guide for the possible initial manual alignment procedure which would be carried out by an astronaut during the fabrication phase of the array. The protruding photoconductive sensor would provide a convenient target by which the position of the incident laser beam is readily observed, and the subsequent adjustment will use the center of the laser beam as a reference to align the center of the photoconductive sensor, establishing the flatness of the overall array.

The separation between the sensor elements is determined by the beamwidth at the closest photoconductive sensors to the rotating beam system. The separation should be much smaller than the beamwidth such that the laser beam can be incident simultaneously on both sensor elements and result in two counterbalancing signals of sufficient magnitude to permit the nulling bridge circuit to be adequately sensitive at the alignment position. Since most helium-neon lasers have exit beam diameters of the order of 1 mm, the separation between sensor elements should be roughly 0.1 mm. This implies that photolithography and vacuum deposition techniques will probably be required to define the photoconductive elements. A clean flat surface, preferably glass, would provide an adequate substrate for the deposition and, as will be discussed later, also provide

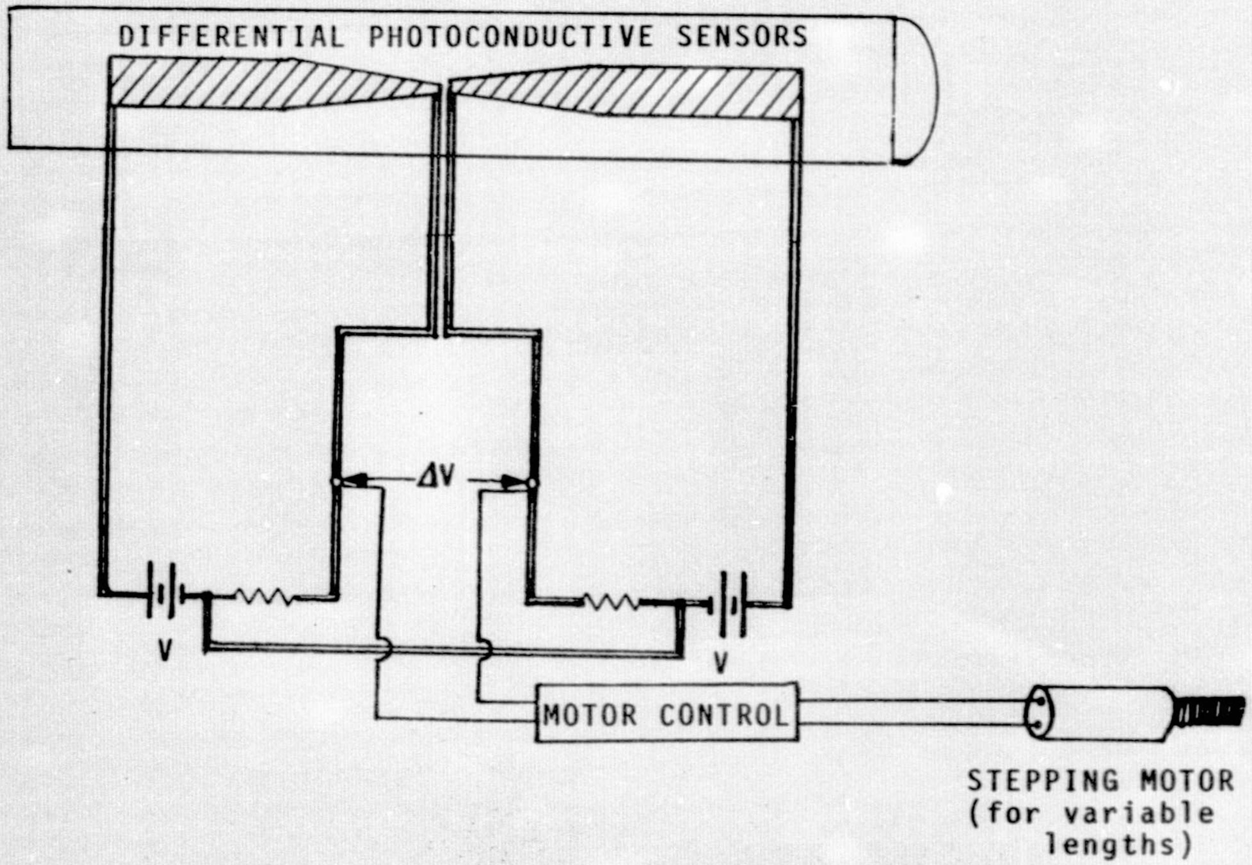

Figure 24. Differential Voltage for Directional Motor Drive

the means of focusing the laser light by including a reflective coating at the opposite end of the optical sensor.

One multiple sensor configuration might retain the redundancy aspect by combining a cluster of sensors onto one glass rod support with its respective reflector backing, as sketched in Figure 25. In this manner, the effective optical blockage cross-section is substantially decreased, the converging optical reflector system is more efficient since the illumination aperture is larger, and the alignment of more than one sensor is simplified because the gaps are all defined simultaneously during one deposition with one photomask.

9.2 Tapered Tips

A further refinement of the photoconductive sensor element is to shape the element to increase sensitivity near the null or centered position. As was shown in Figure 24, the tips of the elements near the center are tapered in shape and truncated. The reason for selecting this particular shape is to increase resistance near the separating gap which is the center of the sensor. By increasing this resistance, the voltage differentials near the null position are enhanced and greater sensitivity is therefore achieved.

Another reason why a tapered tip is necessary is that the sensor must have the capability for operation close to the laser source in addition to operating at 500 m. Since the exit laser beam without collimation is approximately 1 mm in diameter, the tip must be of the same width to decrease the resistance enough to generate a respectable voltage signal when the laser beam is aligned with the gap.

The actual dimensions of the tip will be governed by the size of the collimated beam used but the same principle holds for a larger collimated beam. The final optical sensor element should have a photoconduction profile along its length determined by its geometric shape such that the equivalent voltage signals to the variable-length motor drives are comparable for the full range of operation out to 500 m. This analysis would necessarily include the measured laser beam divergence with distance and the resistivity of the photoconductive material. Since the thickness of the deposited photoconductive material is uniform, the geometric shape can thus be calculated. This approach is necessary only if

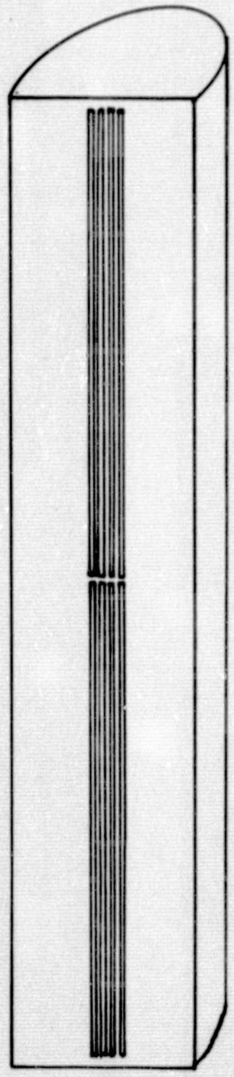

Figure 25. Cluster of Sensors on One Glass Rod

a common optical sensor design is used. Otherwise, different tapers can be used for a family of sensors, classified primarily by the radial distance it is located from the laser system.

9.3 Reflective Convergence

It would be very desirable to use commonality in the overall sensor design since this would simplify fabrication and servicing. At extreme distances, due to beam broadening, there is a large reduction in incident radiant energy on the critical photoconductive elements, and this substantially reduces the subsequent voltage imbalance signals which control the electric motor drives. One technique which compensates for some of this beam spreading loss is a light concentration scheme which would refocus the energy. An earlier suggestion employed a converging lens system which would reduce the effective beam diameter at the extreme ranges; however, it is not feasible in a practical sense and alternate solutions to the problem were therefore investigated.

Using the cylindrical symmetry of the glass rod on which the photoconductive sensor is mounted, it is not unreasonable to devise a reflector which also converges the beam to a focal line parallel to the axis of the cylinder. The glass rod, which provides the physical structure for mounting the photoconductive sensor, might then be designed to provide the proper curvature for a reflecting surface. An obvious choice would be parabolic, though it would be expensive. A more reasonable and readily available glass rod would be semicircular in cross-section. Both cross-sections are sketched in Figure 26. The flat surface would contain the photoconductive sensor and would face the rotating laser beam. The round back surface would be coated with a highly reflective metallic coating such as gold with a chrome or nickel flash coating. At close ranges, the rotating laser beam would slowly sweep by the thin photoconductive sensor element. Due to the cylindrical symmetry, the reflected light should remain in the same plane as the laser beam reference. At longer ranges, the collecting efficiency is greatly enhanced by the rear curved surface which reflects light toward the rear surface of the photoconductive sensor, much like the integrating spheres of infrared detectors but in two dimensions.

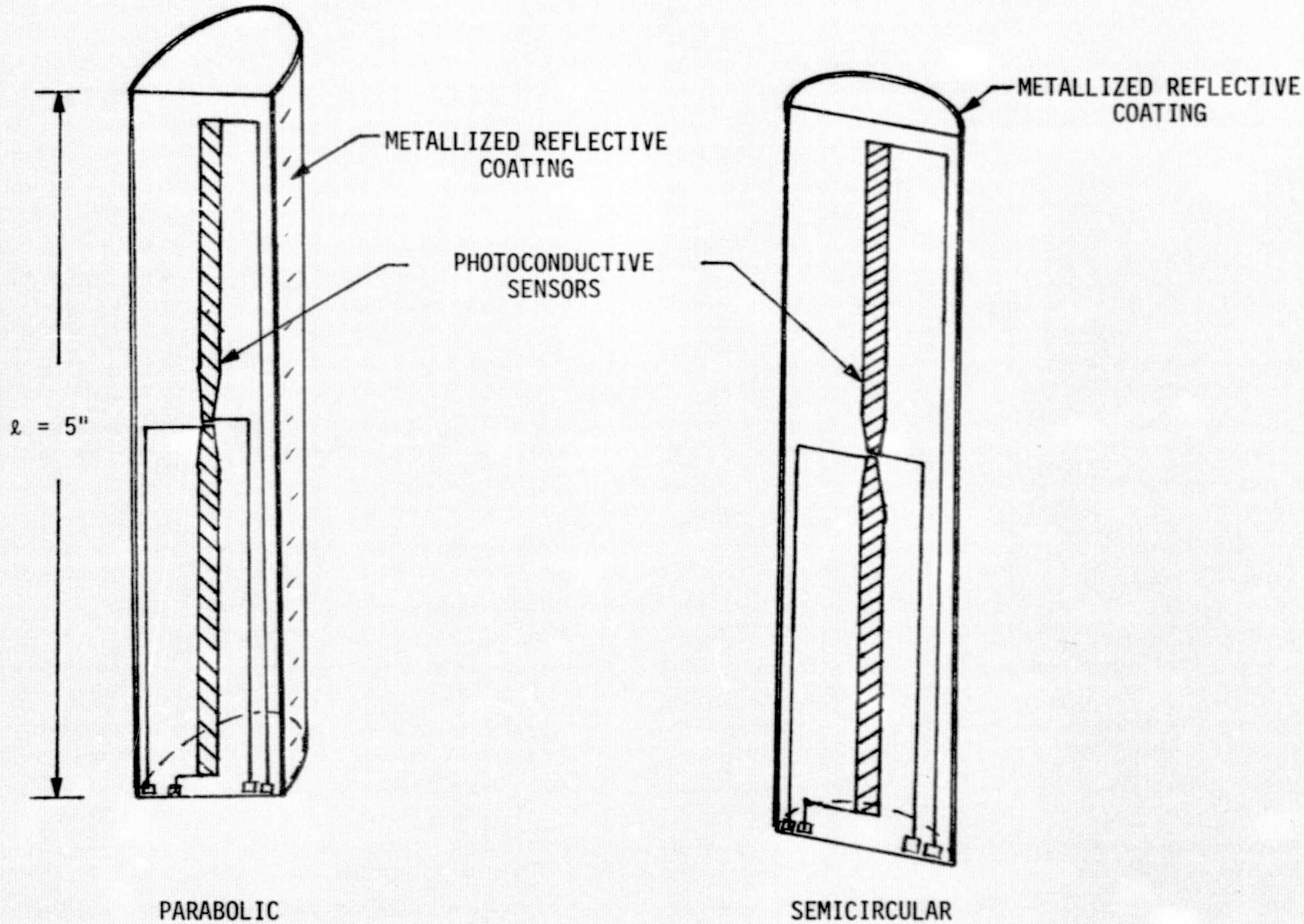

Figure 26. Photoconductive Sensors with Reflectors on Glass Rods

9.4 Optical Filtering/Antireflection Coating

Since the dominant helium-neon light wavelength is 6328 angstroms, it is possible to deposit an antireflection coating over the flat photoconductive sensor surface. By using additional multilayer materials, the covering could also serve as an optical filter to exclude all other wavelengths, a feature which prevents tracking spurious signal sources. The multiple thin-film coating also serves to provide physical protection of the photoconductive material and to reduce outgassing of volatile components.

Antireflection coatings are commonly used at dielectric-air interfaces to improve the transmission of light into the dielectric materials. For example, a magnesium fluoride film is deposited on camera optics to eliminate reflections. The only requirements for this quarter-wave case are that the dielectric constant of the antireflection coating is the square root of the product of the two outside materials and the thickness is equivalent to a quarter-wavelength in the coating. Mathematically speaking, the electromagnetic wave impedances are matched for maximum power transmission.

If optical filtering properties are also desired, the situation becomes more complex since the subject of multiple layer thin films is not straightforward. Very sharp filter characteristics, however, are routinely manufactured on glass plates for laser optics and it is therefore feasible to combine this technology with the optical sensor design to filter out undesirable light signals. Again, the design involves a lengthy calculation of translated impedances, but the experimental monitoring of the thin film depositions with a helium-neon laser system greatly expedites the process. And finally, for protective purposes, an outer layer of a glass frit (i.e., silicon dioxide) provides a wear coating that also seals the sensor material from outgassing.

It should also be noted, incidentally, that the nulling resistive bridge circuit motor drive avoids false signal lock since a diffuse light background will inherently compensate itself by maintaining a null condition. However, the sensitivities of the photoconductive sensors are degraded with background illumination such that prudent engineering design would incorporate some optical filtering.

9.5 Multilayer Film Deposition Technique

The deposition of multilayer thin films should be accomplished with a helium-neon laser monitoring scheme which directly measures the appropriate film thicknesses in order to maximize the transmission of laser light into the sensor. This technique is an extension of the rather complex mathematical analysis required to optimize the optical filtering properties.

In general, it is difficult to monitor the thicknesses of deposited thin films with a high degree of accuracy. Crystal thickness monitors commonly used are not adequate for multiple thin film depositions and are therefore excluded. The most feasible method is to use a helium-neon laser source which is at precisely the wavelength of use to be normally incident on the optical sensor itself, as sketched in Figure 27, and measure the amount of back-scattered radiation. This implies that the minimum reflection condition indicates maximum absorption into the sensor. The exact thicknesses desired are mathematically determined since the impedance relationships are heavily dependent on the thicknesses. Thus, by using the back-scattered radiation as a monitor, one might deposit, for example, a dielectric like magnesium fluoride until minimum reflection occurred, then deposit a protective layer of silicon dioxide during the same pump-down to protectively coat the sensor. This latter deposition, depending on the thickness of the wear coating desired, would continue until another minimum reflection condition is detected. The reflection monitor typically measures a cyclical behavior with increasing thickness so that this technique guarantees maximum transmission.

9.6 Pin Connector Interface

The electrical connection of these photoconductive sensors can be made by a pin-and-socket arrangement similar to electronic tubes. A base cap containing the appropriate number of pins and attachment leads will simply be bonded to the glass rod supporting the photoconductive sensor. Wires can be soldered to connect the lead such that the photoconductive sensor is then inserted into the socket containing the biasing circuitry and the motor drive. Servicing is readily accomplished by simply removing the malfunctioning sensor and replacing it. Slotted slides can slip

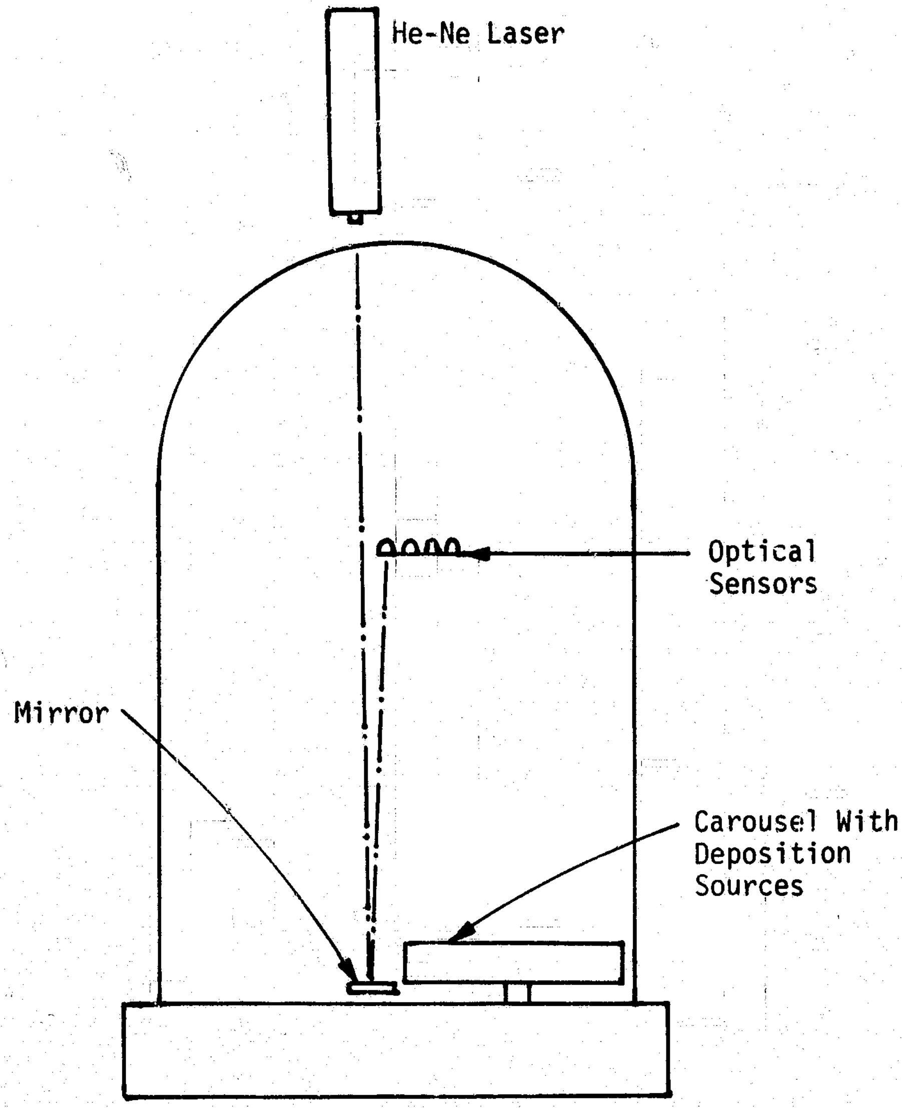

Figure 27. Multiple Thin Film Deposition with He-Ne Laser Monitor

over the edges of the sensor base cap to assure uniform locking pressure on three sides of the parabolic or semicircular sensor. The locking mechanism must be precise since the alignment is dependent on the flatness of the plane on which the optical sensors are located.

A multiple sensor cluster can provide redundancy using only one socket to minimize optical blockage cross-sections. Each optical sensor, however, controls an independently operating motor drive circuit. Since only one base socket is required, only one corresponding connector is needed to facilitate assembly. A four-sensor cluster configuration is shown in Figure 28 with the slotted lateral adjustment capability where the socket can slide to a new position with a clear view of the laser.

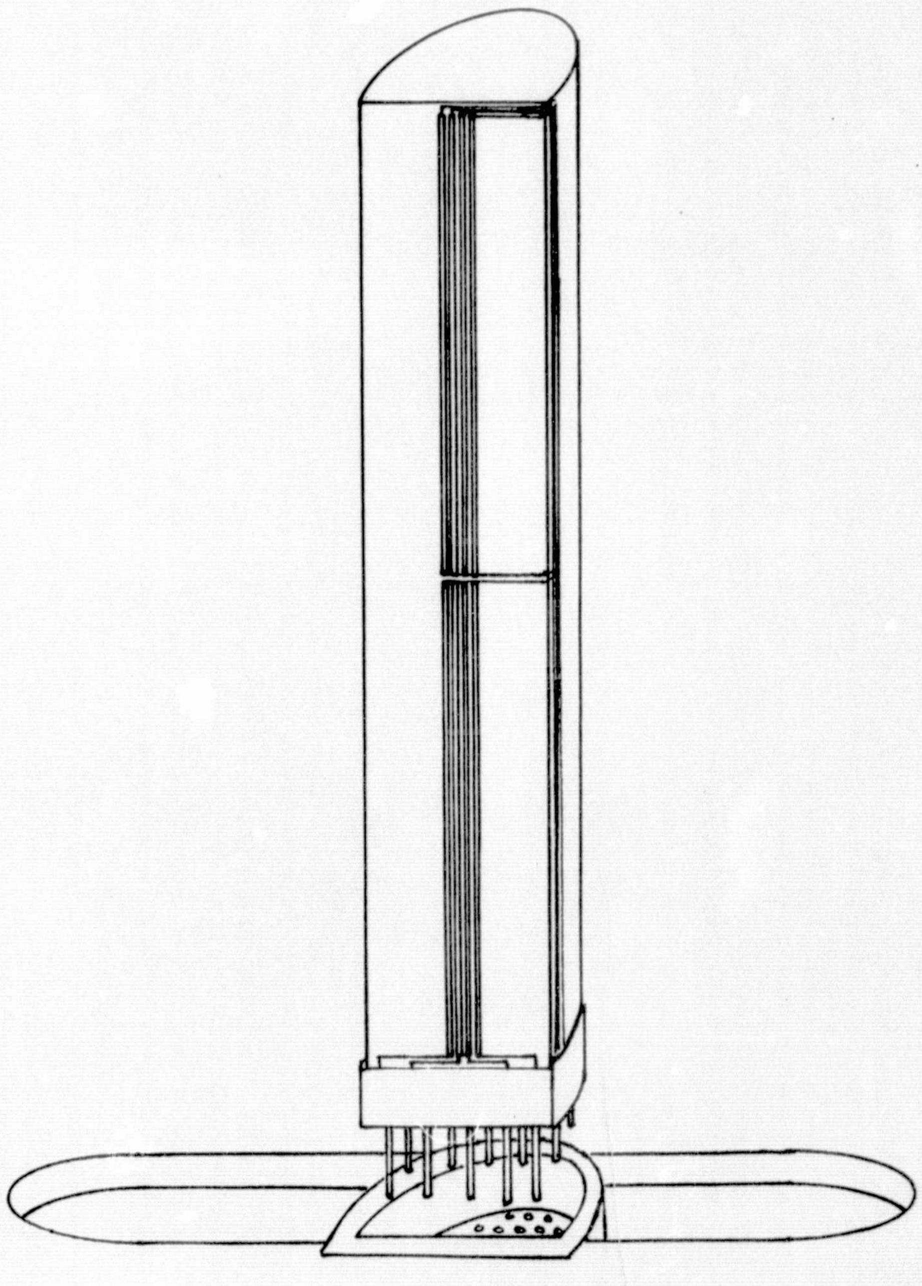

Figure 28. Cluster of Sensors in Movable Socket

10.0 OPTICAL SENSOR EFFECTS ON THE RADIATING ARRAY

As presently envisioned, the photoconductive sensors will be mounted on very thin dielectric cylindrical rods which project out perpendicular to the face of the subarray at each position of the three-point supports: the central universal ball joint attachment and the "azimuth-elevation" attachments. The sensors will be located on the array side of the structure to avoid the blockage effects of the supporting trusses. Since they are normal to the radiated electric field vector, each sensor can be described as a simple dipole on a ground plane, shown in Figure 29.

10.1 Skin Depth Considerations

The analogy of the sensor to a dipole arises primarily because of the metallic reflective coating on the back of the glass rod and the resistive photoconductive film and related thick-film leads composing the sensor. On the basis of skin depth, these metallic films are probably "translucent" since, at 2.45 GHz, the skin depth for aluminum is 2.5×10^{-4} cm (2.5 μm or 25,000 angstroms). For the helium-neon laser wavelength, the equivalent skin depth is 38 angstroms. Therefore, this large skin depth thickness discrepancy can be taken advantage of by depositing reflective coatings less than 1000 angstroms thick. Similarly, if the photoconductive layers are of the order of 2000 angstroms thick, the 2.45 GHz radiated power will not interact much with these sensors.

10.2 Dipole Positioning

The location of the optical sensor cluster is important to the amount of possible interaction of the sensor to the radiated power of the MPTS. By definition, the relationship of the slots of the array are periodic, being at least an integral number of half wavelengths apart. At 2.45 GHz, the free space wavelength is 4.8 inches, so the positions of maximum electric field have a periodicity of 2.4 inches. Each individual sensor with its separate reflector is about 0.25 inch wide, but a multiple sensor cluster of four would be about an inch wide, with the sensor elements centered and probably less than 0.25 inch wide. Therefore, it might be possible in both cases to place the sensors in a position of minimum electric field, thereby minimizing interactions.

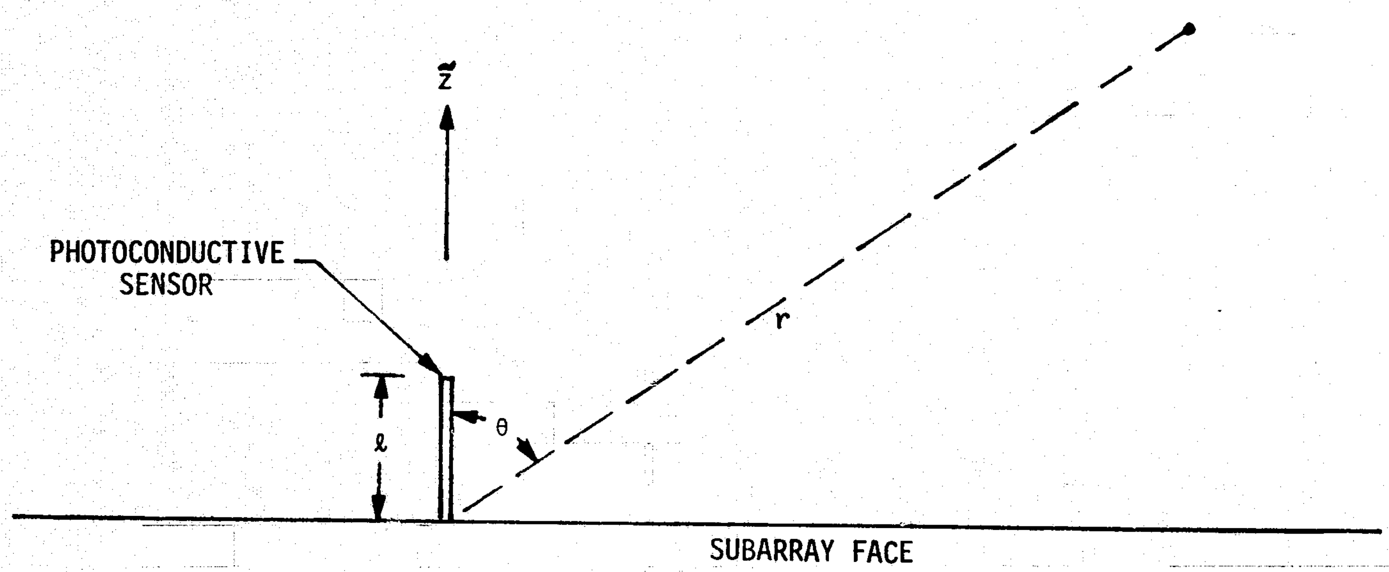

Figure 29. Dipole on a Ground Plane

The criterion for sensor positioning, then, is to locate it an odd number of quarter wavelengths from the adjacent radiating slots at the edges of the subarray.

10.3 Dipole on a Ground Plane

The relationship of a radiating dipole on a ground plane, using the nomenclature given in Figure 29, is

$$E_\theta = \frac{j \eta I_m}{2\pi r} e^{-jkr} \left[\frac{\cos (k\ell \cos\theta) - \cos k\ell}{\sin \theta}\right]$$

The electric field vector, then, is strongly dependent on the orientation of the dipole with respect to the electric field and the length of the dipole. By reciprocity, the interaction can be related from the radiated electric field of the array to an effective dipole. By using this equation to justify some design considerations, minimal interaction will be sought since it is extremely desirable for the optical sensors to be completely isolated from the overwhelming amounts of RF power being radiated.

10.4 Conductive Surface Perpendicular to the Electric Field

The primary design consideration to achieve isolation is that the optical sensors will be perpendicular to the array face and therefore the electric field vector. An electric field can exist normal to a conductive surface but not tangent to it. Referring to the relationship of a dipole on the ground plane, $\theta = 0°$ is the orientation of the radiated electric field vector from the subarray when the sensor is normal to the subarray. The numerator in the brackets then becomes 0 and little mutual interaction occurs between the sensor and the radiated power.

10.5 Optimum Length Considerations

A more devious design consideration uses the length of the dipole to minimize interaction since boundary conditions determine resonance effects for electromagnetic waves. If $\theta = 90°$ and the length of the sensor is chosen to be a multiple of λ, then $k\ell = (2\pi/\lambda)n\lambda = 2\pi n$, where n is an integer; then cos $2\pi n$ is always 1 and the numerator is again 0, which makes $E_z = 0$, so that even the orthogonal polarization component is not coupled. If the frequency is 2.45 GHz, then $\lambda = 12.24$ cm or 4.82 inches. Thus, the

length of the photoconductive sensor is about 5 inches long for minimal mutual coupling, which is also reasonable if the laser beamwidth spreads to approximately 3 inches in diameter at the edge of the large array 500 m away from the centrally located rotating laser system.

10.6 RF Fence

If, after all these precautions are taken, there is still some interaction of the sensors and the radiated power, then an RF fence might be considered. The RF fence in this particular case would electromagnetically shield the entire optical sensor except for the front illuminated aperture which would remain open to view the laser beam.

The RF fence consists of a slotted metal cylinder which is enclosed at the top, as shown in Figure 30. In effect, a cylindrical cavity is achieved with the dimensions determined by the criterion that the electric field at 2.45 GHz is zero along the longitudinal axis where the sensors are aligned. Using the boundary conditions that resonance cannot occur for a diameter of 0.75 wavelengths, the cylindrical diameter is made 3.6 inches wide. The optimum height is 1.25 wavelengths or 6 inches, which also minimizes the possibility of resonance in the cavity. The metal cap on the top reduces the effects of diffracted energy being back scattered from the lip of the cylinder. As a further precaution, a grid of thin wires equally spaced along a window of transparent material provides additional RF isolation, yet permits the transmission of the laser beam for active alignment.

The inner wall of the cylinder would be painted with an appropriate space-qualified black paint to avoid the problem of scattered laser light.

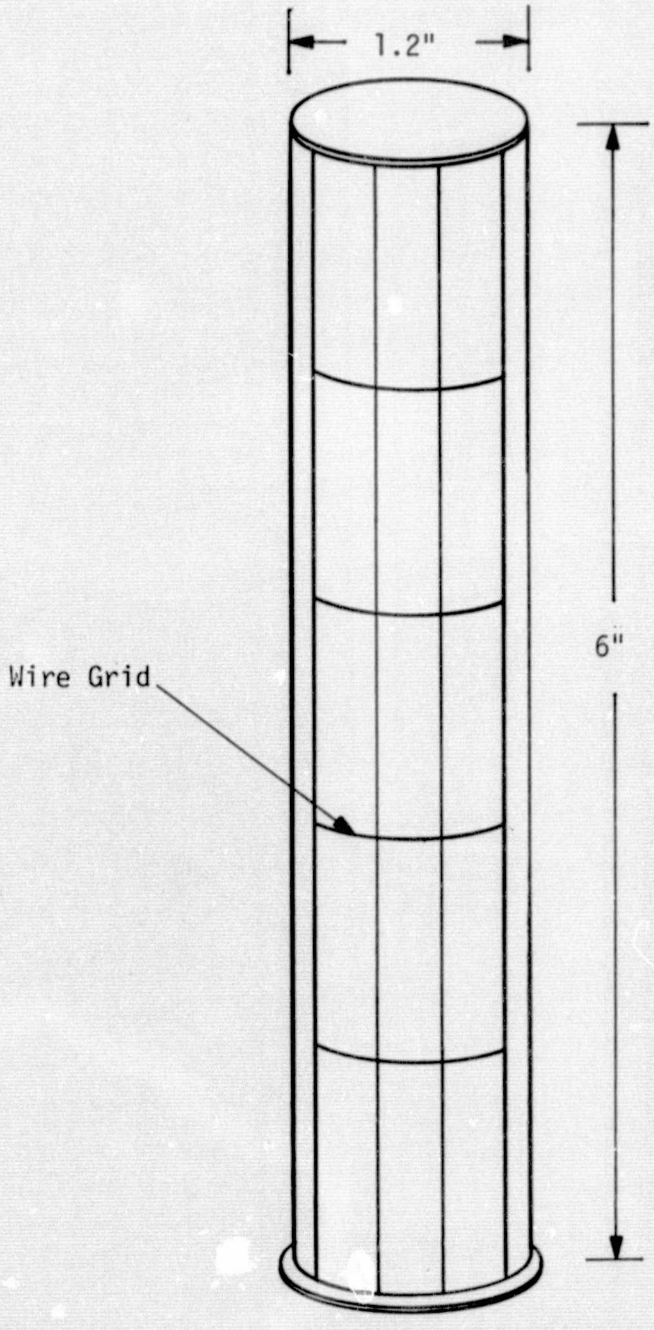

Figure 30. RF Fence - Cylindrical Metal Cover With Gridded Wire Laser Window

11.0 ELECTRIC MOTOR DRIVE

An electric motor is probably the most efficient means of controlling lengths for the variable-length mechanisms which control the tilt of the subarray. The desirable features include low power consumption, mechanical locking, high mechanical resolution, reliable operation and reversing capabilities.

11.1 Differential Voltage Motor Drive

The nulling resistive bridge circuit is sketched in Figure 31. Only one voltage source is required to bias both circuits to eliminate problems with voltage imbalances. Figure 32 shows the laser beam sweeping past the photoconductive sensor. Assuming that the laser beam is uniform in power density, then any asymmetrical illumination will create a voltage imbalance in a Wheatstone bridge since the photoconductive resistances in the two elements will be different from each other. The greater the area of sensor illumination, the greater the decrease in resistance of that element. The polarity of the voltage imbalance indicates the direction that the variable-length motor drive must move in order to attain the centered null condition when the voltage differential is zero. When the beam is centered, little power is dissipated since the biasing resistances are large and the electric motor is deactivated. Three cases of sensor illumination are illustrated in Figure 33. The laser beam sweeping by the left element generates a large positive voltage signal since it is located far from the gap. The centered laser beam creates two opposing small voltage signals which null out with a net zero voltage, indicating alignment. The right-hand laser beam path on the right element results in a smaller magnitude signal, being close to the gap, but of negative polarity. Thus, both distance and direction of offset can be readily determined, much like a radar monopulse tracking system using phase information. Amplitude variations of the signals resulting from the radial distance from the sensor can readily be normalized by adjusting the gains of appropriate amplifiers in the motor controller.

These voltage signals will have to be processed prior to activation of the motor controls because of the variable rotation rate of the laser beam system. If rapid rotation occurs, the nulling bridge circuit

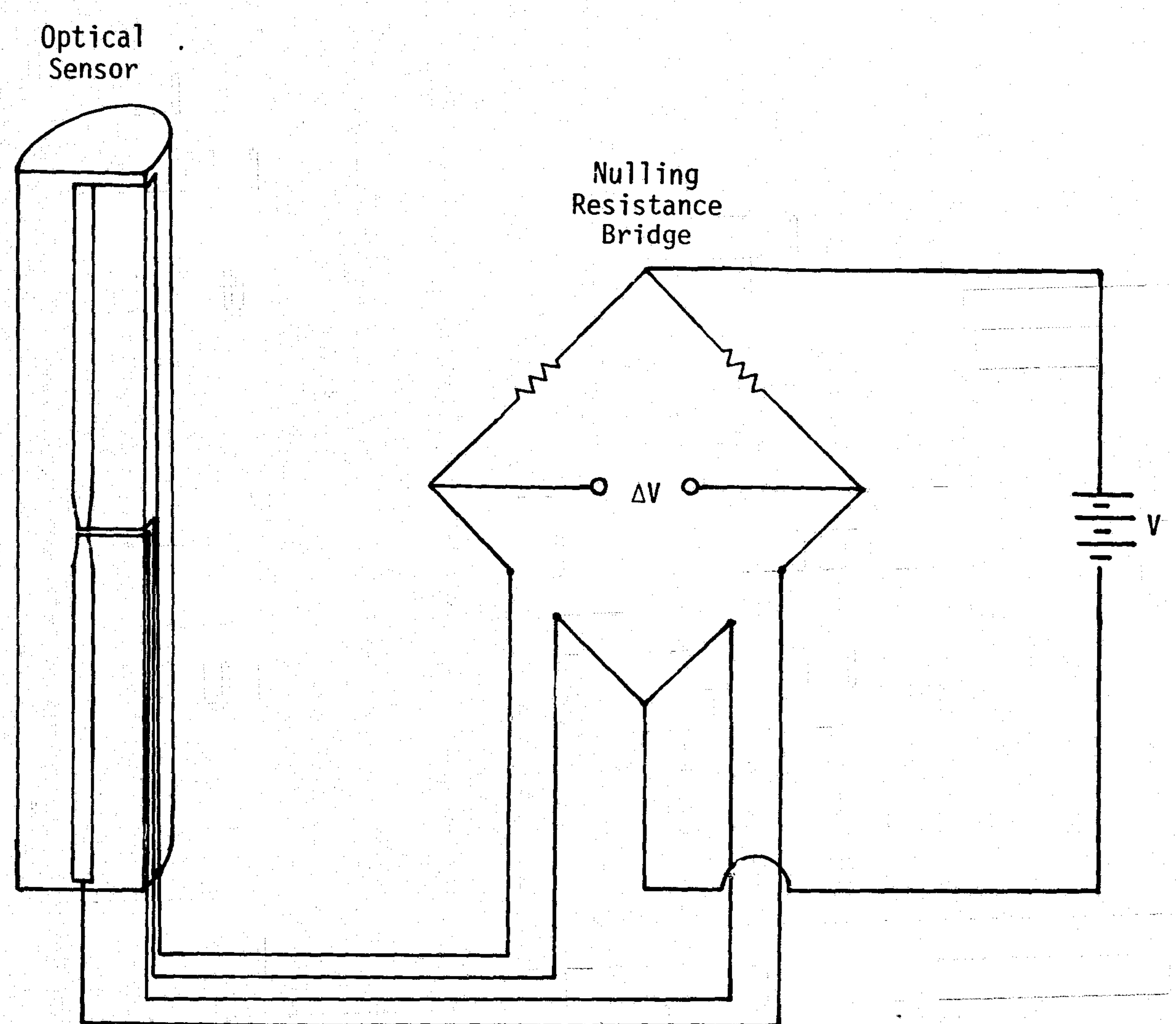

Figure 31. Differential Voltage Derived From a Common Voltage Source

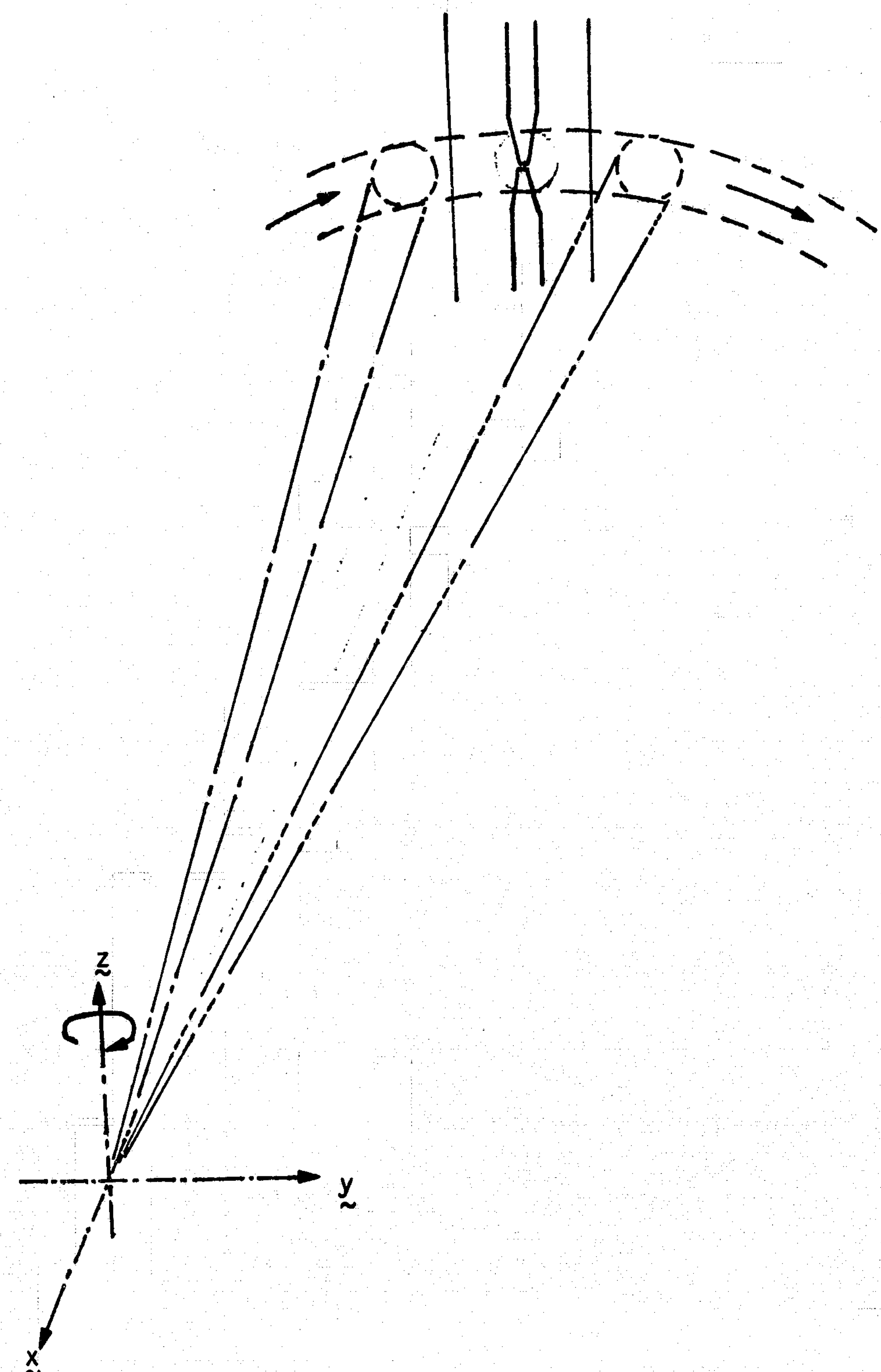

Figure 32. Sketch of Rotating Laser Beam Sweeping Past Photoconductive Sensor

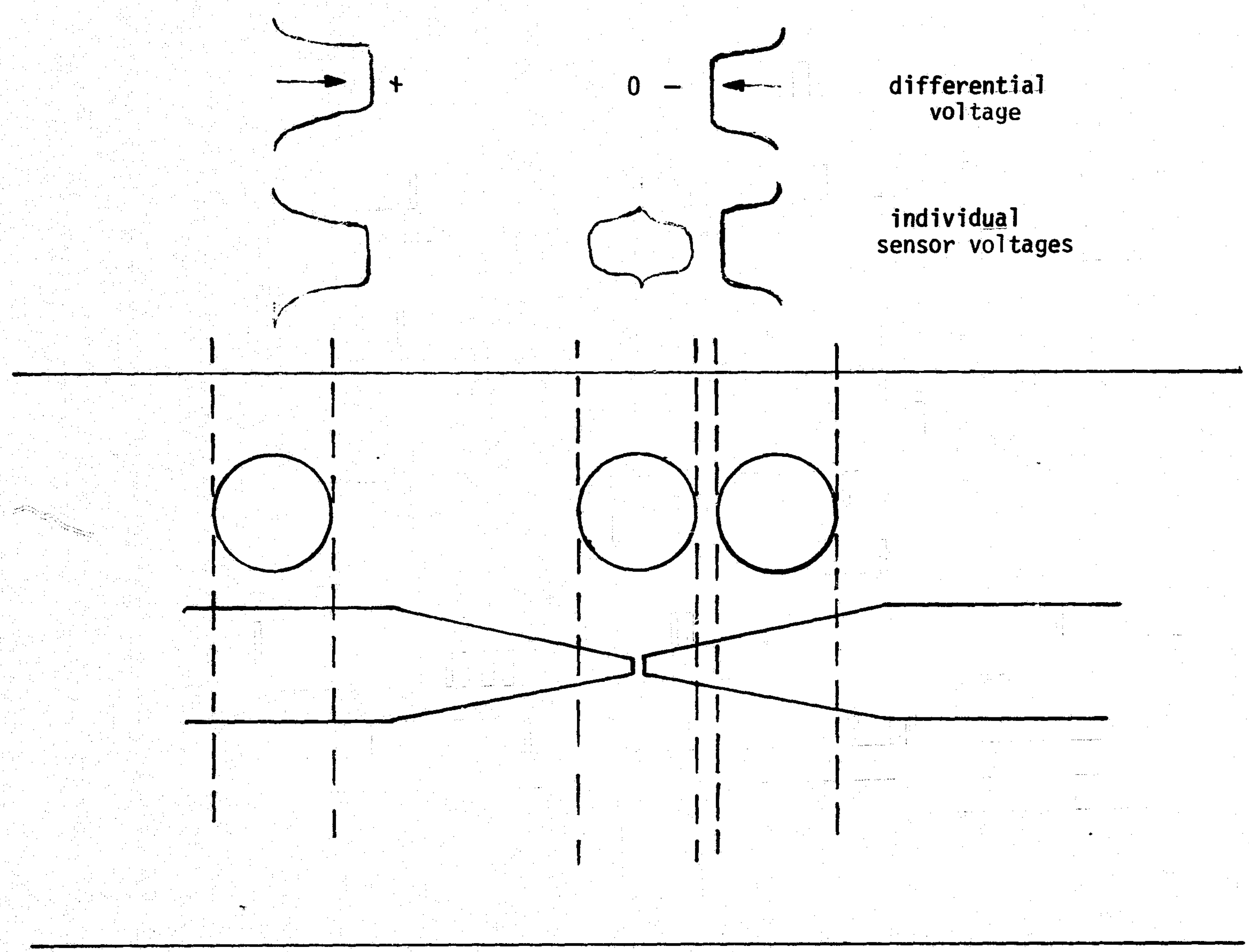

Figure 33. Laser Reference Planes Impinging Upon the Photoconductive Circuit

must respond to short voltage pulses, which is difficult when relatively large biasing resistances are used to reduce power consumption. On the other hand, if slow rotation rates are used, the voltage pulses will be stretched out but the alignment is not updated as often. Since the optical sensors are 5 inches long and the beam is about 3 inches in diameter, the operational alignment range is about 4 inches before the optical sensor loses the laser beam. Under normal conditions, the structure should not experience such drastic misalignments but, anticipating an unusual occurrence, some preventive precautions may be considered.

11.2 Redundant Laser Reference Planes

During the discussion on redundant laser systems, the possibility of operating more than one laser system under emergency conditions was suggested to provide additional laser sources to maintain a reference plane, even though the laser planes are not exactly coincident. If they are aligned within 4 inches at the extremes, the motor drives will be able to approximately correct for rapid structural changes, at least to move the subarrays in the proper direction, to keep the sensors in the alignment range.

11.3 Search Mode

Another technique might consist of a search mode which, when activated, will tilt the subarray towards the laser and move the center strut cyclically up and down until the laser beam reference is reacquired. This latter search mode, if deemed necessary, would have to be implemented only on the outer subarrays where the probability of mechanical distortion with respect to the laser is greatest.

11.4 Signal Integration

Another more practical means of generating sufficient differential voltage signals to drive the motors is to use signal integration. The low-level/short-duration signals can be stored over a preset interval and combined to produce the amplitude voltage necessary to trigger the motor drive. Such integrate-and-dump circuits are commonly used in radiometer circuits to smooth out or average fluctuating signals and improve the signal-to-noise ratio input which, in this case, is sent to the motor

controller.

The DC voltage output can be amplified and the amount and direction of motion determined by using a tilt algorithm developed earlier which relates radial distance from the laser and the differential voltage polarity and magnitude. If it is possible to use this algorithm technique, the motor drive signal processing would be much more efficient than the more standard offset approach where, as in nutating or monopulse tracking systems, only the direction of offset is detected and small incremental corrections are periodically applied until alignment occurs.

11.5 Stepping Motors

Stepping motors are logical candidates for this alignment application since they incrementally step rotations, an obvious advantage for controlling distance with a variable-length mechanism. The steps arise from magnetic detents which provide metastable locking positions. By reversing the polarity of the driving voltages, it is possible to reverse the rotational direction and thereby change the length of the variable-length mechanism to reverse the subarray tilt orientation. By using the tilt algorithm, a microprocessor in the motor controller can determine the number of steps required to align the subarray by the magnitude of the integrated voltage signals.

12.0 ACTIVE ALIGNMENT OPERATION

The active alignment mechanisms have been described in detail. Some of the other considerations that should now be discussed are the philosophy of operation, verification of alignment and flatness, and a shadow masking monitoring technique.

12.1 Continuous or Occasional Operation

The necessity for active alignment procedures can be determined only by actual experience in a space environment, but the capability to initiate active alignment should be incorporated into the structural design of the subarray mount so that, when the need arises, it can be readily implemented. Since there is little history of large structures in space, most of the deleterious effects can only be surmised and adequate compensation precautions taken. This approach is especially feasible for the alignment of the MPTS since the flatness of the array surface is critical to the proper operation of efficient power transmission to earth.

The question of continuous or occasional operation of the active alignment system really reduces to what is found in practice to be necessary. Provisions to operate in either mode should be available. If proper design practices are followed, reduced power consumption in the continuous mode would permit constant operation. On a reliability basis, however, occasional operation might be preferred, especially since the system has a 30-year design lifetime. Even though redundancy is extensively employed and maintenance ease is emphasized, sporadic use might be reasonable.

12.2 Verification of Flatness

In light of the question of occasional alignment, a means must be available for detecting misalignment. One way is to note an abnormal reduction in power received by the rectenna. Another way might include operation of the active alignment scheme and monitoring the motor currents of the variable-length mechanisms as they adjust to the rotating laser beam plane. Although this technique is easily implemented if only the single electric motor drive bus is monitored, the minimum number of 21,000 variable-length motors makes individual motor current monitoring

difficult to isolate the exact location. Also, if the motor for some reason has an open circuit and no current flows, a false indication of alignment would exist. A separate independently operating mechanical means of detecting flatness or indicating the location of a failure is desirable.

12.3 Shadow Masking

One independent means of verifying the flatness alignment is to use a shadow masking technique, sketched in Figure 34, which is based on the premise that, if all the open apertures of properly positioned masks are aligned, a collimated source can be detected at the opposite end which, in this case, is the other end of the array. For example, if the rotating laser beam used for active alignment is also used for flatness verification, a set of black nonmetallic masks with slotted openings in them will transmit the laser light, if properly aligned, to a photodiode sensor at the edge of the array. If these 350 photodiode sensors ring the perimeter of the array, optical detection by all of the photodiodes would indicate that flatness is maintained. If, however, one of the arrays was tilted, the laser beam would be incident on the blackened portion of the mask and would therefore be blocked. This blockage, detected by the absence of an optical signal, would indicate misalignment of the array.

More complex versions of this technique to locate the precise position of the misalignment can be readily formulated since angle and distance measuring systems using GaAs laser diodes are commercially available such as on the Hewlett-Packard 3820A Electronic Total Station, an extremely sophisticated theodolite. Simplified versions using the space within the service corridors underneath the subarrays can also locate misalignments by simple grid intersection deduction by relating the two perpendicular error signals. If there are 7000 subarrays, then 170 lasers and detectors would suffice, with 85 lasers and detectors on each adjacent side.

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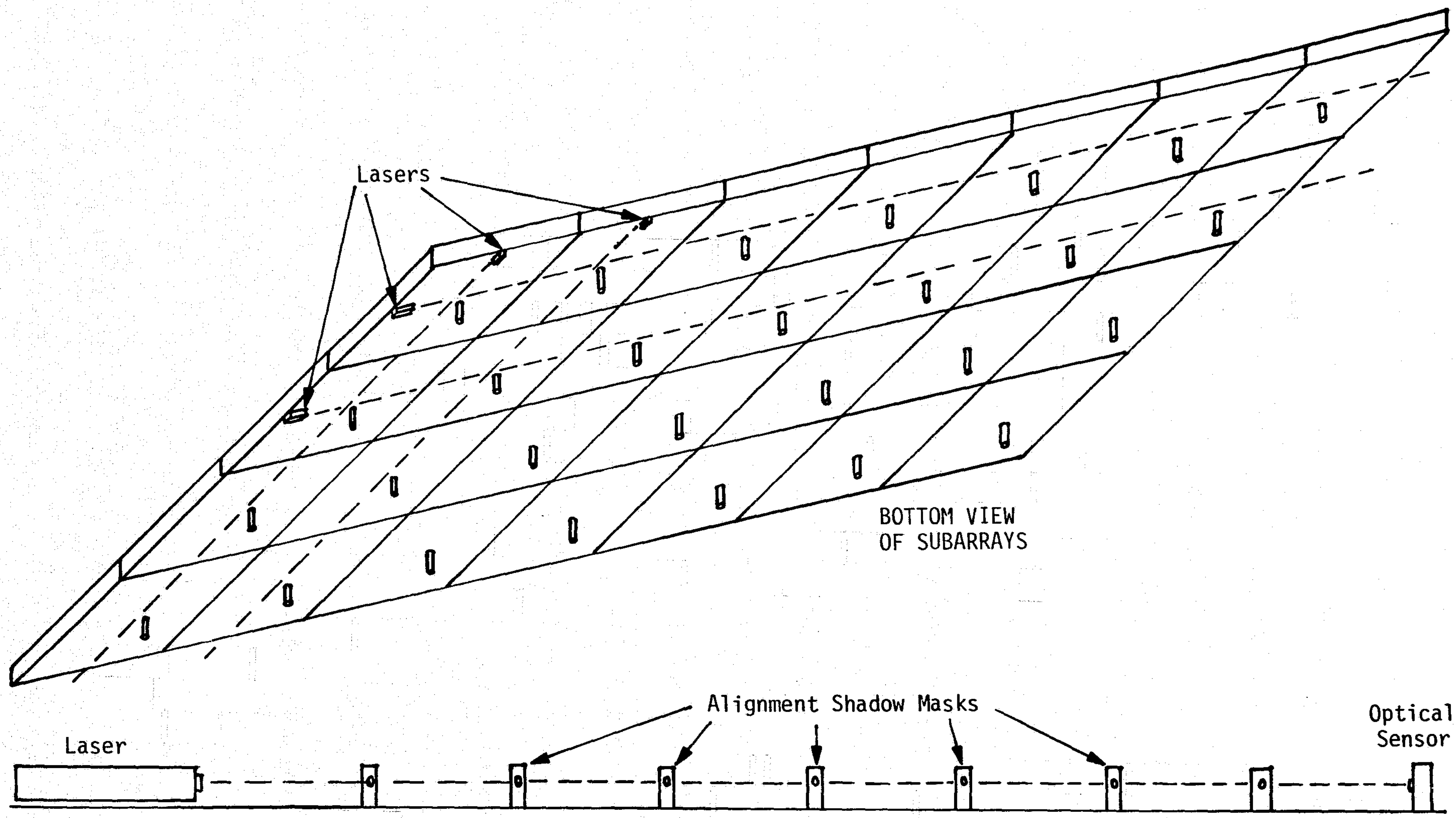

Figure 34. Shadow Masking Concept

13.0 ARRAY MONOPULSE POINTING TECHNIQUE

The pointing of the array of the MPTS must be done accurately to maximize the overall beam efficiency of the radiated power to earth. A theoretical assessment of the slope tolerance is 1 arc-minute, which is difficult to attain for such a large structure.

A retrodirective pilot beam phase conjugation technique is being developed to electronically steer the main beam towards a pilot beam reference located at the center of the rectenna. This technique electronically corrects for the refractive influence of turbulance in the earth's atmosphere by detecting the phase of the received pilot beam, comparing it to a central phase reference distributed to each power module and then transmitting the phase conjugated microwave power derived from solar energy back to the rectenna almost instantaneously.

In order to reduce dependence on the rather complex and costly retrodirective pilot beam system which provides fine tuning, it would be reasonable to investigate supplementary means of pointing which will mechanically point the array in the desired direction to simplify the phase conjugation problem. This section outlines a four-element monopulse pointing system to accomplish this coarse pointing task, with the electronic steering compensating for the short-term fluctuations of the turbulant atmosphere.

13.1 General Description of Monopulse Pointing

The essential feature of the monopulse system is that a plane phase front (which is a spherical wave front at extremely long distances) arrives at the large array simultaneously if the array is pointed at the pilot beam source. By comparing the phases from a number of detectors located on the surface of the array, it is possible to determine the direction and amount of pointing error, and this information can be used to actively track the pilot beam. Thus, four coherent receivers at the center of the sides of the MPTS array with a phase comparator at a central location can be used to actively point the array itself.

Monopulse pointing is a commonly used technique for microwave radar systems to acquire and track targets. In many respects, it resembles electronic steering in that the effective main beam of the antenna is slightly tilted by utilizing the additional information derived from

the phase shifts introduced by a target offset from the main beam. By adding and subtracting the various combinations of signals, the offset direction is known. For example, if the pilot beam reference signal was centered on the main beam, all the signal phase incident on the monopulse elements would be identical, and the sum channels in both vertical and orthogonal horizontal planes are maximal. If, however, the pilot beam was offset in the vertical plane, both vertical plane sensors would detect phase differences, the magnitudes being angularly proportional to the offset. A tracking system then compensates for this error signal by realigning the antenna in the proper direction to maximize the vertical plane signals again.

A focusing system is normally used for tracking radars to increase the gain of the antenna, and angular magnification results from the focusing into the centrally located feed elements. In the case of the MPTS array, no equivalent focusing occurs so that the monopulse system must use the full dimensional extent of the array to magnify the phase differences. This adds complexity in that accurate phase references must be supplied to the four monopulse elements, but this problem has been addressed in the phase conjugation scheme and is therefore assumed to be solved.

The implementation of a monopulse pointing scheme requires the development of a new system which can perform this phase difference detection. A possible approach is outlined in this section, and a key subsystem in this concept, the baffled hood, is described which provides isolation between the transmitted microwave power and the received pilot beam reference signal.

13.2 Baffled Hood Concept

The baffled hood isolates the received pilot beam signals from the concurrently transmitted microwave power such that the coherent pilot beam phase information can be used to point the array towards the effective source of the pilot beam by the principle of reciprocity. If the averaged phase signals arriving at the four widely separated baffled hoods are correlated and found to be identical, the main beam of the radiating array should also be pointed towards the pilot beam source.

The baffled hood is simply a means of obtaining a high degree of

directionality by the use of a physical hood and microwave absorbers to provide baffling, much like an optical baffle uses apertures and black paint to achieve collimation. A sketch of a possible baffled hood is shown in Figure 35, where the hood is shown located below the plane of the radiating array to reduce the possible reception of unwanted microwave power that could saturate the pilot beam receiver. As presently conceived, the antenna system would consist of a large parabolic dish to increase the gain of the system and a feed horn that is polarized orthogonally to the MPTS power polarization to provide additional cross-polarization isolation. The walls of the hood would be lined with microwave absorbers to absorb glancing radiation, and the open end of the bottom of the hood serves to allow passage of any reflected power not absorbed. Therefore, any radiation that is not aligned with the main beam of the pilot beam antenna is not received. Reflections are minimized by the absorber and open-ended hood. Any undesirable radiation from spillover or reflections is then either absorbed, transmitted through, or defocused such that it reflects out of the aperture of the hood. For example, if some of the back-scattered MPTS power, which is relatively small because of the 10 dB Gaussian illumination taper, enters the baffled hood from the side, part of the power would be absorbed or reflected through the hood and the other part illuminating the parabolic dish would be defocused from the center feed and be reflected back toward earth. The pilot beam, however, being normally incident on the baffled hood, would be focused by the parabolic reflector into the feed and the phase information utilized to point the array.

The microwave absorber lining the walls is a Brewster-angle impedance matching design that, in the longitudinal ridge configuration, absorbs both orientations of linear polarization. The absorber, an iron-filled epoxy, is space-qualified. The material, CR117, made by Emerson and Cumings, is cast in ridges and has a relatively high dielectric constant, which reduces the thickness requirements substantially.

In order to obtain coarse pointing information, one or more of the four monopulse elements can possibly have a secondary monopulse system. This secondary monopulse system would be a subsystem of one of the monopulse elements and, by using similar phase difference information from four feeds in the one baffled hood, the proper pointing direction can be

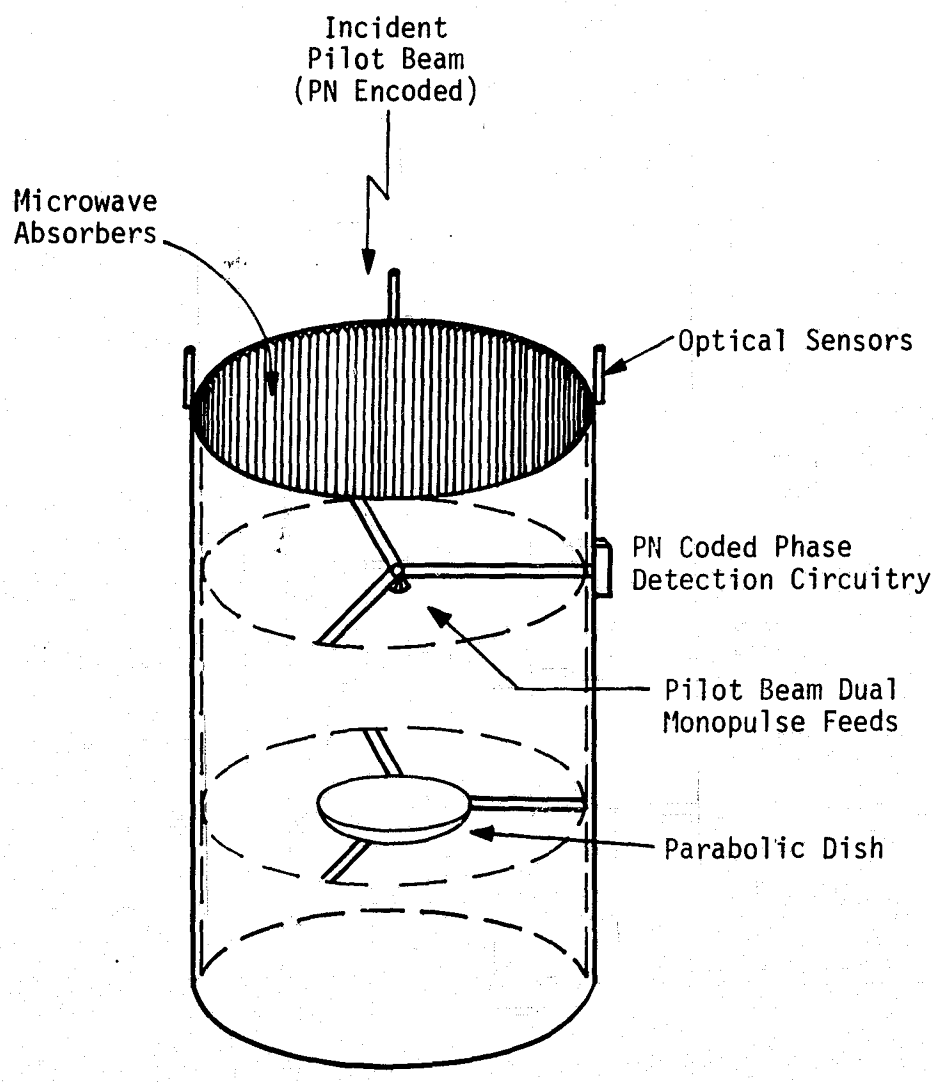

Figure 35. Baffled Hood Dual Monopulse Pointing Elements

determined. This dual monopulse system then provides both coarse and fine pointing capabilities.

In order to avoid ambiguities arising from a sinusoidal CW signal, the pilot beam should be pseudonoise-coded and other secure communication methods employed to prevent jamming. Using correlation techniques, phase-matching accuracies can be greatly enhanced. Since the retrodirective pilot beam system again already includes these features, implementation is not difficult. Averaging of the received phase information might be found necessary if the spatial extent of the ionospheric turbulance regions are of the order of the array dimensions. Only the phase conjugation scheme can, by electronic steering, track rapidly fluctuating refractive processes in turbulent media, the amount and periodicity of which are not clear at this time.

13.3 Location of the Monopulse Elements

Since the array is mounted on a gimballed yoke type of support with the two rotational axes through the center of the array, it is important to position the monopulse elements such that the two orthogonal tilting directions are mutually independent to minimize the amount of iteration that is required to complete the pointing procedure. And once pointing is attained, subsequent adjustments should be simplified by having to activate as few tilting mechanisms as possible. Figure 36 indicates the probable locations of the monopulse elements assuming this rotating gimballed yoke support.

13.4 Flatness Reference Alignment for the Monopulse Element

The flatness alignment of the baffled hood with the array itself is important since it must also be referenced to the array face. Since the laser beam reference plane establishes the alignment for the subarrays, the baffled hood could be similarly aligned if it could use the same optical sensors and mounting scheme. Since it need not be above the array face, it can use a shorter center cylindrical support and be located just above the secondary structure in the same plane as the service corridors. The optical sensors would then project by extensions from the baffled hood aperture into the laser beam plane.

The flatness criterion at the extreme ranges is again limited by

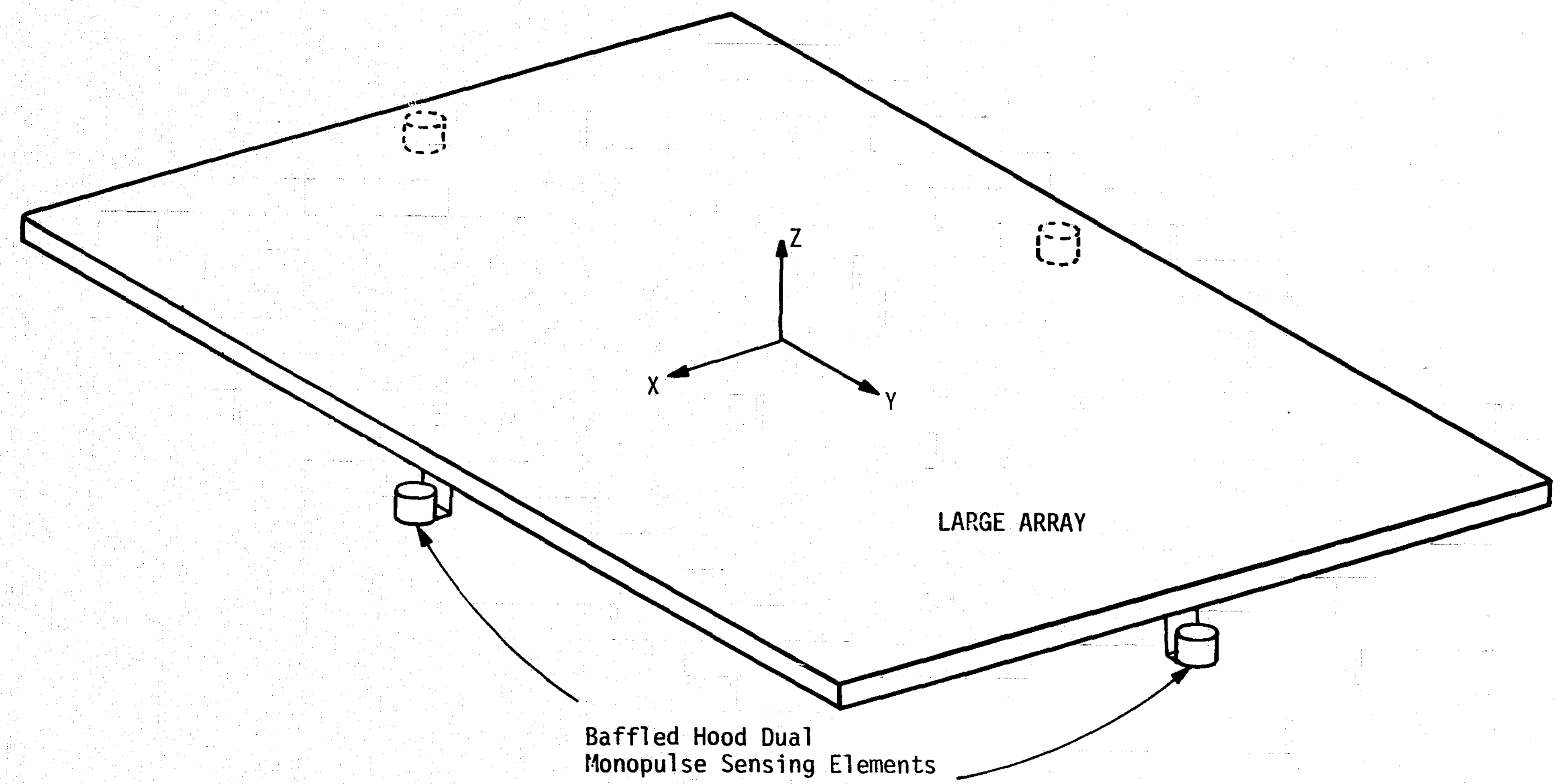

Figure 36. Sketch of the Placement of the Baffled Hood Dual Monopulse Pointing Elements

the laser beam broadening effects, but the only real requirement for the monopulse elements, since only phase information at the four monopulse element locations are used, is that consistent beam centering occur. And the only real limitation on this method, even with nonuniform beam intensities, is that the laser beam diameter be smaller than the total length of the optical sensor. If the laser beam diameter is larger than the sensor, the tolerances on the nulling resistive bridge beam centering technique increase to the point where it is unusable.

13.5 Pointing Accuracies

Assuming the flatness of the subarrays has been achieved and the monopulse pointing system indicates the simultaneous phase reception of a PN-coded pilot beam, the pointing requirement should be satisfied. The pointing accuracy of this scheme can be determined by comparing the average value of the fluctuating phases of the received pilot beam over the extended array which is 1 km wide. For example, if one monopulse element was 90° off in the averaged phase value, the pointing error would be of the order of 1.2 inch ($\pi/2$ at 2.45 GHz) over 1 km, which is an error of 6 arc-seconds. Therefore, the pointing accuracy of 1 arc-minute, at least on a theoretical basis, will be readily satisfied.

14.0 WAVEGUIDE CANDIDATES FOR THE MPTS

As part of the study for the active alignment for the MPTS array, the question of the use of metallized composite waveguides was introduced as a lightweight alternative to the standard metal waveguides, which would add considerable mass and therefore contribute to higher transportation costs since the SPS was to operate in geosynchronous orbit. Since metallized composites have only previously been used for antenna reflector applications in space (e.g., Nimbus G/Seasat Scanning Multifrequency Microwave Radiometer), its projected application in high-power waveguides was uncertain.

This section discusses some of the advantages and disadvantages of metal and metallized composites, then introduces a possible third candidate for consideration, a hybrid metal/composite waveguide, that attempts to satisfy the otherwise conflicting requirements in a technically viable manner.

14.1 Metal Waveguides

The metal waveguides are superior for almost all applications except for operation in deep space where weight is a problem. This weight aspect holds especially true when large amounts of waveguides are required, as is the case of the 1 km square MPTS array. In order to minimize RF losses and therefore heating, good conductors must be used, and most good conductors are metals such as gold, silver, copper (brass) and aluminum. Besides weight, the other disadvantage is the coefficients of thermal expansion which, in the space environment, can be severe if the waveguides get either too hot or too cold. The radiating slots then lose their physical relationship with the termination, probably a short circuit, and the maximum electric fields will subsequently not be positioned at the slots.

The alternative to the good conductor is an alloy like Kovar which has a negligible coefficient of thermal expansion but is lossy. A gold inner plating still makes this combination too heavy to be practical. Thin gold-plated stainless steel waveguides are often used for cryogenic applications and they may be considered as a candidate.

Of all the metal waveguides, aluminum--being lightweight and a fairly good conductor--probably satisfies most of the requirements.

However, it again suffers from the thermal expansion problem and therefore some system trade-off studies must be undertaken to determine feasibility.

14.2 Metallized Composite Waveguides

Metallized composite waveguides are being considered on the MPTS array to save weight and minimize the effects of thermal expansion. There are a number of design problems that should be considered if such an approach is pursued.

First, the composite will probably be graphite epoxy, which has a low coefficient of thermal expansion. The uncured resin problem was discussed earlier, and it is understood that this composite will have to be studied more extensively to demonstrate feasibility.

Second, the adhesion properties of aluminum to graphite epoxy have not been well established. At least one vendor uses multiple layers of aluminum and a dielectric such as silicon dioxide to avoid the problem of flaking of thickened layers of vacuum-deposited metallic films; this method must be avoided. The aluminum must be deposited within a waveguide, which implies difficulty of inspection and film thickness verification. The corrugation approach shown by Boeing might be feasible if the waveguide walls are securely attached and no RF leakage occurred.

Third, the use of "expansion joints" might be employed to prevent peeling of the metallic film under thermal stress. Since a standing wave waveguide radiating stick is used, it is possible to use sections of metallic film. These sections would be connected by a thinner segment of metallic film such that, if thermal stresses occurred, separation would be limited to this thinned section. The thinned sections would be located at positions of least interaction with the standing wave such that it would cause little or no attenuation. The thermal expansion effects would thus be limited in extent and therefore peeling, which would be catastrophic for the high powers employed here, would be minimized.

Fourth, a roughened composite interface can be used for improved adhesion.

And finally, the outside radiating face of the waveguide should also be metallized to provide a ground plane for the radiating array

since graphite epoxy is anisotropic and is not a good conductor.

14.3 Hybrid Metal/Composite Waveguides

Because of the critical function of the radiating waveguides composing the subarrays, the use of metallized composite waveguides should be critically questioned. The only obvious characteristic is the lightness in weight, but the added complexities introduced might outweigh this advantage. The transmission of extremely high power levels, the desirability of maintaining low losses, and the need to provide good heat dissipation all favor the use of metallic waveguides.

A compromise alternative can result from designing the basic waveguide fabricated from extremely thin-walled aluminum with the structural rigidity being provided by composite materials. If the exterior of the aluminum waveguide remains exposed, the ground-plane necessary for proper operation of the array inherently exists.

Figure 37 shows a candidate hybrid metal/composite waveguide structure where ridged perimeter sections surrounding the waveguide provide attachment points to the graphite-epoxy composite material. Any stresses in the aluminum due to thermal changes will be forced to be distributed along the entire waveguide stick since the negligible expansion coefficient composite will not allow it to move. The ridge sections also serve to physically strengthen the waveguide walls since they will be very thin. If the ridges are sequenced to be in between the radiating slots, they should not affect the aperture fields or, therefore, the antenna pattern.

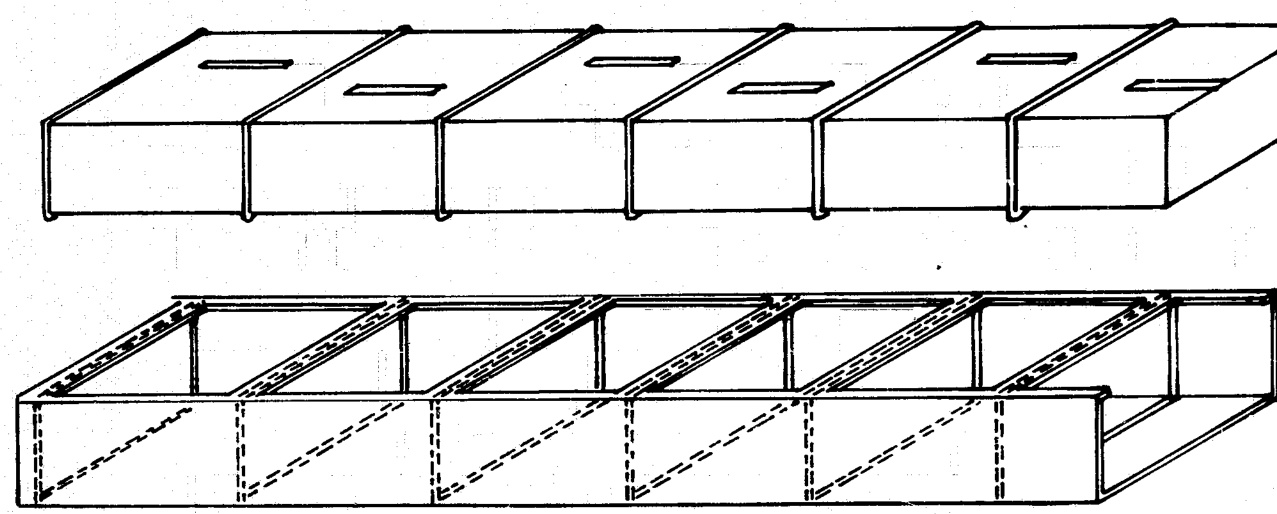

Figure 37. Candidate Hybrid Metal/Composite Waveguide Structure